Improving the Parametric Method of Cost Estimating Relationships of Naval Ships

by

Ungtae Lee

B.S.E., Electrical Engineering
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Signature of Author: ……………………………...…………………………………………………
Department of Mechanical Engineering and System Design and Management
May 10, 2014

Certified by: ………………………………………………………………...……………………
Eric S. Rebentisch
Research Associate, Sociotechnical Systems Research Center
Thesis Supervisor

Certified by: ……………………………………………………………………………………...
Mark W. Thomas
Professor of the Practice of Naval Construction and Engineering
Thesis Supervisor

Accepted by: ……………………………………………………………………………………..
Patrick Hale
Director, System Design and Management Fellows Program
Engineering Systems Division

Accepted by: …………………………………………………………………………...………...
David E. Hardt
Chairman, Department Committee on Graduate Studies
Department of Mechanical Engineering

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ABSTRACT

In light of recent military budget cuts, there has been a recent focus on determining methods to reduce the cost of Navy ships. A RAND National Defense Research Institute study showed many sources of cost escalation for Navy ships. Among them included characteristic complexity of modern Naval ships, which contributed to half of customer driven factors. This paper focuses on improving the current parametric cost estimating method used as referenced in NAVSEA's Cost Estimating Handbook. Currently, weight is used as the most common variable for determining cost in the parametric method because it's a consistent physical property and most readily available. Optimizing ship design based on weight may increase density and complexity because ship size is minimized. This paper will introduce electric power density and outfit density as additional variables to the parametric cost estimating equation and will show how this can improve the early stage cost estimating relationships of Navy ships.

Thesis Supervisor: Eric S. Rebentisch
Title: Research Associate, Sociotechnical Systems Research Center

Thesis Supervisor: Mark W. Thomas
Title: Professor of the Practice of Naval Construction and Engineering

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BIOGRAPHICAL NOTE

LT Ungtae Lee was commissioned in 2005 through the Reserve Officer's Training Corps program at Duke University as a submarine officer. After completion of Navy Nuclear Power Training and Submarine Officer Basic School, he reported onboard the USS ALBUQUERQUE (SSN706) in September 2006 to become the Electrical Officer. After completion of his submarine qualifications, he served as the Assistant Engineer and Assistant Weapons Officer. He completed a total of three deployments to the Mediterranean Sea, Southern Command, and Pacific Command. After his sea tour, LT Lee reported to Commander Naval Forces Korea (CNFK) in Seoul, South Korea in September 2009 where he served as the Exercise and Plans Officer and later served as the flag aide for CNFK/CTF-76. LT Lee was part of the U.S. Naval staff and response watch team during the attack on the Korean ship, ROKS Cheonan (PCC-772), artillery shelling of Yong-Pyong Do and the death of Kim Jung Il. After his shore tour, LT Lee transferred into the Engineering Duty Officer community and reported to MIT in April 2012. LT Lee holds a Bachelor of Science and Engineering in Electrical. LT Lee's decorations include the Navy Commendation Medal and other individual and deployment awards.

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- Laurent Deschamps, President at SPAR Associates, Inc.
- Dane Cooper, Technical Director, Cost Engineering & Industrial Analysis Naval Sea Systems Command
- LT Aaron Dobson, MIT 2N, fellow graduate student
- Kevin Carpentier, Senior Vice President, SCRA Applied R&D Maritime & Manufacturing Technologies Division
- Duke Vuong, Program Manager, Producibility at General Dynamics NASSCO

1. Introduction

1.1. Background

There has been much focus on understanding why Navy ships cost so much and why costs continue to rise. Even as far back as 1939, the Government was wondering why Navy vessels cost so much. The Secretary of the Navy, Ray Spear wrote a memo back to the Chief of the Bureau of Supplies and Accounts to answer the question of "Why do naval vessels cost so much?" with the following reasons:[1]

> 1. The cost of naval vessels increase with the progress of marine engineering and naval construction.
>
> 2. There has been a marked increase in the horsepower of present day ships compared to older ships of the same tonnage.
>
> 3. There has been an improvement in the character of the material used and in the construction of naval vessels. For example, the steel is of a higher quality and requires special treatment. It is used to a greater extent in both hull and deck protection.
>
> 4. Costs are relative only for vessels of the same design built during the same approximate periods.
>
> 5. Costs are affected in the same way that the cost of living is affected from an economic and social point of view.
>
> 6. Reasonable cost of Naval vessels can only be determined by a complete knowledge of cost of current labor and material prices and production methods on the detailed items making up the group costs along the technical lines of work and material.
>
> 7. More stress and care must be taken in approving estimates to make sure that they are reasonable and held to in the cost of production.
>
> 8. When contracts are negotiated the question of costs should be investigated and a detailed knowledge of approximate costs obtained.
>
> 9. When you pay the full price for the best you can buy the cost will always be high.

[1] Arena et al., "Why Has the Cost of Navy Ships Risen?".

Even after 75 years many of these reasons still apply. This paper will address cost estimation (reasons 6, 7 and 8) and will attempt to improve on the current early stage weight based cost estimating relationship (CER).

1.2 Origin of Idea

Interestingly, exploring cost estimating was not the original thesis idea. The initial approach was to explore and benchmark the Korean shipbuilding industry since they are one of the leaders in shipbuilding. The potential existed to observe the Korean shipbuilding best practices and obtain new insights on improving costs and obtaining construction efficiencies of naval ships. This thesis was not pursued because of access restrictions to the cost and man-hour data from the international shipyards. Then, Dane Cooper, the technical director of Cost Engineering and Industrial Analysis at NAVSEA suggested the idea of exploring cost estimating and finding non weight-based CERs. His suggestion and support from the cost estimating group at NAVSEA marked the start of this thesis.

1.3 Objective of Thesis

This thesis will explore a new method of early cost estimation. It will explore the use of the parametric method and try to improve on the current weight based parametric method, using new variables such as power density, outfit density, electric power generation, and shaft horsepower. These will be explained in detail later. Currently, weight is used as the most common variable for determining the cost estimating relationship because it is something that is most readily available particularly at early stages. The NAVSEA cost estimating handbook explains many other factors that play into cost estimation and will be discussed in detail in later sections. Weight is used as a CER because it is a very consistent physical property. But through conversations with cost estimators at NAVSEA, we have learned that weight-based CER is outdated. The current method of cost estimation lags behind the complexity that exists with modern shipbuilding. *What are better indicators that more accurately predict cost estimation? Specifically, what available variables can improve the parametric method of Cost Estimating Relationships?*

We will explore mainly two new types of variables, *Outfit Density* which is defined as outfit weight (SWBS Group 200-700) divided by Total Ship Volume and *Power Density* which is defined by Ships Total Electrical Power Distribution divided by Light Ship Weight. These variables will be defined further later in this paper.

1.4 Implications

The paper hopes to provide an improvement to the current weight-based cost estimating relationship in hopes to provide more accurate and reliable cost information to decision makers for planning and programming purposes as well as system architecture and design tradeoffs within NAVSEA05C. The results of this paper may be useful in the Navy's cost estimating models such as Navy's Product Orientated Design and Construction (PODAC) or in future development in naval ship design software.

2. Shipbuilding Industry

2.1 U.S. Naval Shipbuilding

The US shipbuilding industrial base is heavily dependent on its naval shipbuilding. The commercial shipbuilding, because of its size, cannot compare with the international shipbuilding giants and so the core of US shipbuilding industry lies in the acquisition, construction, repair, and decommissioning of military ships. As demonstrated by the recent construction of the DDG-

1000, the United States produces some of the most technologically advanced warships in the world. As of 2014, there are seven shipyards in the United States building naval ships.

Major U.S. Based Shipyards		
Shipyard	Company	Current Product Emphasis
Bath Iron Works	General Dyanmics Corp.	Surface Combatants
Electric Boat	General Dyanmics Corp.	Submarines
NASSCO	General Dyanmics Corp.	Auxiliaries and commerical
Newport News	Huntington Ingalls Industries, Inc.	Carriers and submarines
Ingalls	Huntington Ingalls Industries, Inc.	Amphibs, surface combatants, Coast Guard Cutters
Austal USA	Austal, Ltd.	LCS and JHSV
Marinette Marine	Fincantieri - Cantieri Navali Italiani S.p.A	LCS

Figure 1. Major US Shipyards[2]

Figure 2. Locations of Major Shipyards in US[3]

[2] Koeing, "Technology and Management in the Global Shipbuilding Industry."
[3] Ibid.

Figures 5 and 6 show the various locations of the naval shipyards in the United States along its coast line. Many of these shipyards started as privately owned yards but were eventually bought out by larger defensive companies such as General Dynamics and Huntington Ingalls.

2.2 Issues in Naval Shipbuilding

The United States produces the most technically advanced and capable naval ships in the world. But issues within the industry has caused cost growth and has threatened the purchasing power for the Navy.[4] Figure 3, from the Office of the Deputy Under Secretary of Defense, shows eleven reasons for cost growth and its corresponding sources. Among the reasons for cost growth is poor estimating.

SOURCES OF COST GROWTH (EXAMPLES)

Reason for Cost Growth	DoD/Navy	Shipyard	Suppliers and Integrators
Procurement instability	✓✓✓		
Immature design at the start construction	✓✓✓	✓✓✓	✓✓
Material ordering, delivery, and schedule delays	✓✓	✓✓	✓✓
Schedule slippage		✓✓✓	✓✓✓
Capability enhancement	✓✓✓		
Poor estimating	✓✓✓	✓✓✓	✓✓✓
Change orders	✓✓✓	✓✓	✓✓
Material and equipment costs			✓✓✓
Poor project management	✓✓	✓✓✓	✓
Unable to recruit appropriate labor		✓✓✓	✓✓
Poorly defined construction specifications	✓✓	✓✓	

Source: ODUSD(IP)

Key:
✓ Some impact
✓✓ Moderate impact
✓✓✓ Significant impact

Figure 3. Sources of Cost Growth[5]

[4] Office of the Deputy Under Secretary of Defense, "Global Shipbuilding Industrial Base Benchmarking Study."
[5] Ibid.

In addition, a study from the Global Shipbuilding Industrial Base Benchmarking Study (GIBBS) in 2005 shows the initial and projected cost growth of 8 ships as seen in Figure 4.

Cost Growth in U.S. Navy Warships					
Initial and Current Budget Request ($ millions)					
Case Study Ship	**Initial**	**Current**	**Difference (%)**	**Projected Additional Growth**	**Total Growth (%)**
DDG 91	917	997	8.7%	28-32	12.0%
DDG 92	925	979	5.4%	9-10	7.0%
CVN 76	4,266	4,600	7.8%	4	7.9%
CVN 77	4,975	5,024	1.0%	485-637	12.3%
LPD 17	954	1,758	84.2%	112-197	100.5%
LPD 18	762	1,011	32.6%	102-136	48.3%
SSN 774	3,260	3,682	12.9%	(-54)-(-40)	11.5%
SSN 775	2,192	2,504	14.2%	103-219	21.6%
Total	**18,251**	**20,556**	**12.60%**	**789-1,195**	**18.10%**

Figure 4. 2005 Cost Growth in U.S. Navy Warships[6]

On average, there is an 18% increase in cost growth for naval ships with the highest cost growth in the lead LPD-17 ship. The GSIBBS study also lists the sources of potential cost growth from the Navy, shipyards, and its suppliers, which includes procurement instability, immature design, scheduling delays, poor estimating, change orders, poor management, etc. [7]

When the actual cost of a particular ship exceeds its budgeted cost, the Navy must compensate by requesting more money or adjusting the number of ships it plans to build. For example, in fiscal year 2005, the Navy budget plan allowed for the procurement of ten ships, but only produced four[8]. The differences in budgeted costs vs. actual cost underlines the importance

[6] Ibid.
[7] Ibid.
[8] Ibid.

of accurate cost estimating models. Inaccurate budget requests can negatively impact the Navy's long term strategic plan for forward presence and defense by reducing the footprint of the US navy abroad.

In addition, lower procurement of ships means that more capability must be installed on existing ships. Ships designed for specific missions such as mine countermeasure may be phased out and Destroyers, Cruisers and other surface combatants will take on more responsibility. Fewer numbers of ships also impact the manpower of the U.S. Navy. To maintain forward presence with fewer ships, many deployments have increased from six months to eight months. This increased up-tempo has put significant strain on the life of sailors and has a direct relationship with the Navy's attrition rate. [9]

Furthermore, the service life of existing naval ships must be extended to compensate for the smaller number of ships being produced. A longer service life requires strengthening critical structural components and weight reduction in some areas. This further increases complexity. As ships are being planned to have longer service life with more capabilities and increased survivability, ship design complexity will increase and may increase the cost of naval ships. Figure 5 shows that the issue of cost growth, if not addressed, can put naval shipbuilding into a vicious cycle consisting of decreased procurements, greater complexity, and additional cost growth.

[9] Fellman, "8-Month Deployments Become the 'New Norm.'"

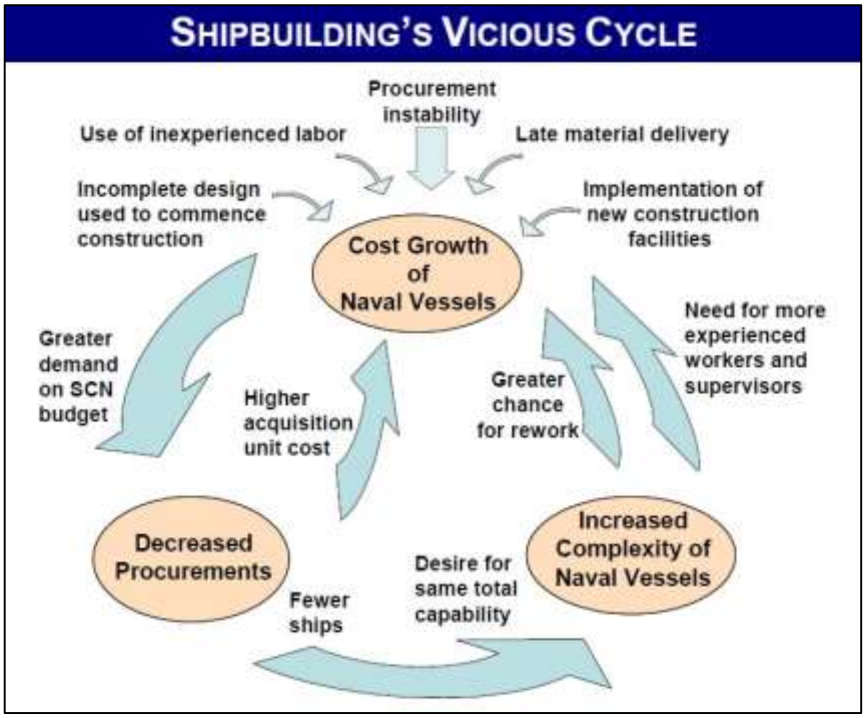

Figure 5. Shipbuilding's Vicious Cycle[10]

3. NAVSEA05C

3.1 Overview and Responsibilities of NAVSEA05C

The Naval Sea Systems Command Cost Engineering and Industrial Analysis Division (NAVSEA05C) is the cost estimating branch of the Navy. This division is the technical warrant holder for cost engineering, which means they are the subject matter experts on cost estimation for Navy ships. Technical Warrant Holders provide leadership and are accountable for all engineering and technical decision-making. They also establish technical policy, standards, requirements and processes including certification requirements, identify and evaluate technical alternatives, determine which are technically acceptable, and perform associated risk and value

[10] Office of the Deputy Under Secretary of Defense, "Global Shipbuilding Industrial Base Benchmarking Study."

assessments, delegate responsibilities in writing to subordinates, engineering agents and other technical organizations, maintain technical competency and expertise to effectively perform missions, and identify both immediate and future resources needed to properly exercise technical authority.[11]

NAVSAE05C's latest published guide is the NAVSEA 2005 Cost Estimation Handbook which is their official cost estimating reference and describes the cost estimating process and supporting techniques for estimators. This living document serves as a reference manual for all Program Office members, business financial managers, sponsors and others who are in various roles and responsibilities of Navy's cost estimation. [12] Figure 6 shows how NAVSEA05C is related to NAVSEA and all its offices below it.

[11] Lawrence, "Basis of NAVSEA Technical Authority."
[12] Deegan, "2005 NAVSEA Cost Estimation Handbook."

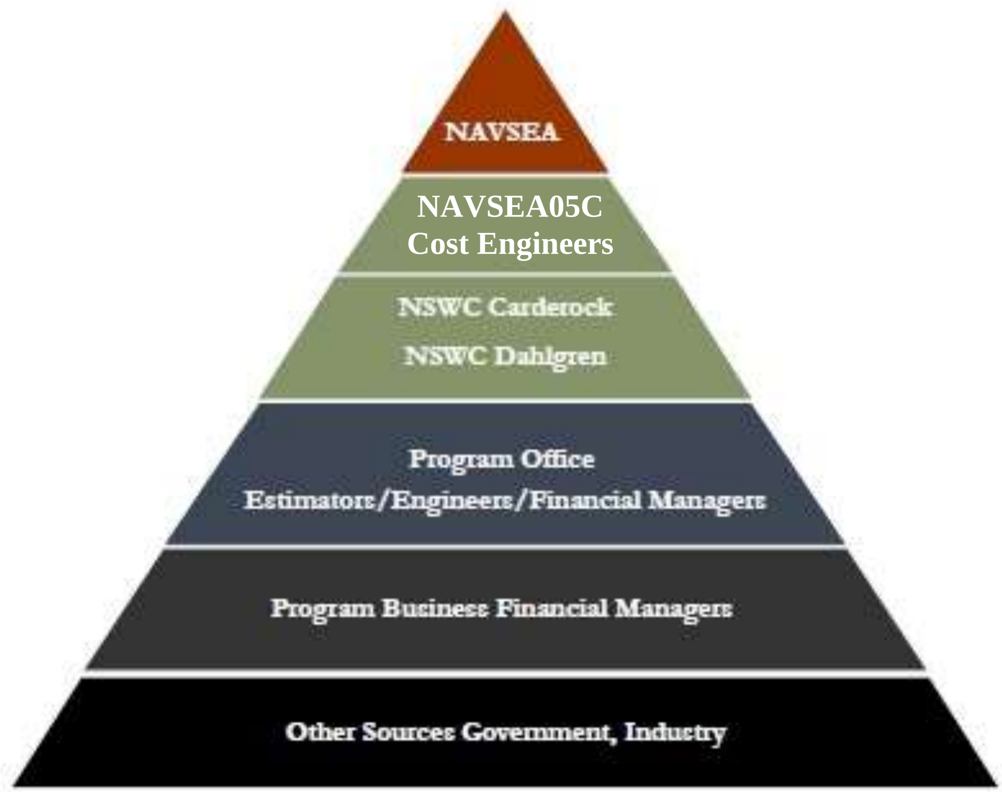

Figure 6. NAVSEA Cost Estimating Community[13]

3.2 Steps of NAVSEA Cost Estimation

3.2.1. Task 1. The Initial Estimate is presented.

To ensure that a solid foundation is met, a team is formed with a lead cost analyst identified. This team reviews the program's mission, objectives, and goals as well as the operating environment. This team will establish the baseline cost from which the estimate can be compared.

3.2.2. Task 2. The Cost Analysis Requirements Description (CARD) document.

This document consists of the program's technical description. Estimators uses CARDs to baseline life-cycle costs and identify any areas that could have a major impact. The CARD

[13] Ibid.

includes such things as, System WBS, Detailed technical and physical description, subsystem descriptions, technology maturity levels of critical components, PM's assessment of program risk, system manpower requirements, system milestone schedule, and acquisition plan or strategy.

3.2.3. Task 3. The Work Breakdown Structure (WBS).

Next, the Shipboard work breakdown structure is obtained. This may also be called the Cost Breakdown structure or a Cost Element Structure. The WBS is an important project management tool since the total cost of the ship is broken down into smaller parts as defined by the WBS. The Navy currently uses the Expanded Ship Work Breakdown Structure (ESWBS) as seen in Table 1. It is used to organize, define, and graphically display all the work items to be accomplished by the project. The ESWBS is important because it is the common shared language between the designer, cost estimator, shipbuilder, and NAVSEA. ESWBS is broken down into seven functional technical groups (GR 100-700) and two groups that deal with integration and ship assembly and support systems (GR 800-900).

Group Number	ESWBS Name	Group Discription
100	Hull Structure	Includes shell plating, decks, bulkheads, framing, superstructure, pressure hulls, and foundations
200	Propulsion Plant	Includes boilers, reactors, turbines, gears, shafting, propellers, steam piping, lube oil piping, and radiation
300	Electric Plant	Includes ship service power generation equipment, power cable, lighting systems, and emergency electrical power
400	Command and Surveillance	Includes navigation systems, interior communications systems, fire control systems, radars, sonars, radios,
500	Auxillary Systems	Includes air conditioning, ventilation, refrigeration, replenishment-at-sea systems, anchor handling, elevators, fire extinguishing systems, distilling plants, cargo piping, steering systems, and aircraft launch and
600	Outfit and Furnishings	Includes hull fittings, painting, insulation, berthing, sanitary spaces, offices, medical spaces, ladders, storerooms, laundry, and workshops
700	Armament	Includes guns, missile launchers, ammunition handling and stowage, torpedo tubes, depth charges, mine handling and stowage, and small arms.
800	Integration/ Engineering	Includes all engineering effort, both recurring and nonrecurring. Nonrecurring engineering is generally recorded on the Construction Plans category line of the end cost estimate while recurring engineering is recorded in Group 800 of the Basic Construction category.
900	Ship Assembly and Support Services	Includes staging, scaffolding, and cribbing; launching; trials; temporary utilities and services; materials handling and removal; and cleaning services

Table 1. ESWBS Names and Group Descriptions[14]

[14] Ibid.

The ESWBS groups are further broken down at the 1-digit, 2-digit, or 3-digit level as seen in Table 2.

Estimating Level	ESWBS Level Example
1-Digit Weight Breakdown	Hull Structure - Group 100, Electric Plant - Group 300
2-Digit Weight Breakdown	Hull Decks - Group 130, Lighting System - Group 330
3-Digit Weight Breakdwon	Second Deck - 132, Lighting Fixtures - Group 332

Table 2. ESWBS Breakdown[15]

This ESWBS breakdown is promulgated in NAVSEAINST 4700.01A and supersedes previous classifications such as the Bureau of Ships Consolidated Index (BSCI), Ship Work Breakdown Structure (SWBS), and MIL-HDBK-881[16]. This ESWBS format is required for all Navy ships since it will be used throughout the ship's life cycle to track the construction project, acquisitions, and a format to communicate scope between review authorities and stakeholders.

3.2.4. Task 4. Ground Rules and Assumptions (GR&A).

In this section, the cost estimator specifies which costs are included and which costs are excluded for the current estimate and future estimates. Some common GR&A's that are included in a cost estimate are, (1) Guidance on how to interpret the estimate properly, (2) What base year dollars and units the cost results are expressed in, e.g. FY13$M, (3) Inflation indices used, (4) Operations concept, (5) Classification to the limit and scope in relation to acquisition milestones, (6) O&S period, maintenance concept(s), (7) Acquisition strategy, including competition, single or dual sourcing, contract type, and incentive structure, (8) Production unit quantities, including

[15] Ibid.
[16] Department of Defense, "Department of Defense Handbook Work Breakdown Structure."

assumptions regarding spares, long lead items, and make or buy decisions, and (9) Quantity of development units or prototype units.

3.2.5. Task 5. Select Cost Estimating Method and Tools.

In the fifth task, the cost estimators select the appropriate cost estimating method and the tools for the specific job. Task 5 is where the actual cost estimating occurs. Within the Navy, the cost estimation is broken down according to ESWBS groups. Each group must select their own cost estimating method and tool depending on what is appropriate for the group and the sum of all the ESWBS groups composes of the total cost estimate. There are four common types of Cost estimating methods. They are, Analogy, Parametric, Engineering Build-up, and Extrapolation from Actuals. Although this paper will focus on the parametric method of cost estimating, it is important to cover the basics of the other major cost estimating methods because they are essential to Navy ship estimation. Figure 7 shows the four common estimating methods and when they are used in the Life Cycle of ship design and construction.

Figure 7. Four Cost Estimating Methods by Life Cycle Phase[17]

[17] Deegan, "2005 NAVSEA Cost Estimation Handbook."

We see that during the very early stages of Cost estimating, even before the concept refinement stage, the Analogy cost estimating methods is used. As more details emerge and more information is available for the cost estimator, a more accurate, bottom-up cost estimation is used. Toward the end of the Ship's Life cycle, we can extrapolate actual cost information and it no longer becomes an estimation.

3.2.5.1. Analogy Cost Estimation Method

The analogy cost estimation method is the earliest cost estimation method. It is a bit more refined than an expert's opinion of the cost of a new ship. It is subjective and historically-based and can be only used if there are comparable ships to obtain a baseline cost model. If a comparable ship has never been produced, as in the case of the DDG1000, then it would be very difficult to obtain an accurate analogous cost estimation. The cost of the historical item must be normalized for content and inflation. Furthermore, in modern ships, the mission packages and mission systems can be a significant portion of the total cost. The baseline cost model must reflect the increased expected cost for the mission packages. In addition, the cost of the analogous ship must be inflation-adjusted to today's dollars. And since the Navy uses the ESWBS system, each WBS element must obtain its own cost estimates and later be summed together to obtain the entire ship's cost estimate. It is important to be able to discuss with experts the validity of the analogous ship especially considering the complexity of ship systems. This is the most subjective portion of cost estimating since we do not exactly understand how much complexity affects costs. For example, it is insufficient to say that because a new program is twice as complex as the analogous ship, the program should cost twice as much. Any new or unusual feature on a new ship, e.g. rail gun, would be somewhat difficult to account for since there is no precedence.

3.2.5.2. Parametric Cost Estimating Method

During the early stage of the ships life cycle, in the concept phase, the parametric cost estimating method is used. Typically a parametric cost estimating method uses a mathematical formula to relate some variable to cost. Historically, weight has been used as the most common ship characteristic/parameter or variable to determine cost. This relationship is called the Cost Estimating Relationship (CER). Although at this stage of cost estimation, non-parametric CER's exist, these other methods are not recommended since they do not rely on historical data to confirm their statistical accuracy. In order to create a CER, the cost analyst must have a good understanding of cost drivers through discussion with engineers and other estimators. And the technical variable must exist and be readily available at the concept stage of the design process. The most common parametric form uses weights as the variable since this is the most consistent physical property that the designer is able to provide to the estimator.[18]

A regression analysis is required to create a CER. Using any number of commercial available statistics software, a least squares best fit (LSBF) is created given the data set. The simplest form of CER is a linear model as defined in equation 1.

$$C = K * W$$

Equation 1

C = estimated Cost of the item

K = cost per unit of material weight

W = weight of item

[18] Ibid.

If other technical variables are available such as power, it would add additional fidelity to the cost equation. It could be added as a multiplicative factor to the basic linear equation.

$$C = \frac{R}{R_S}^{K^r} * (K * W)$$

Equation 2

K^r = cost factor based on unit power rating

R = power rating (e.g., horsepower)

R_S = power rating of baseline unit

Furthermore, if a new material used other than steel such as a new composite material with its own K factor, then a new equation can be used as seen in Equation 3.

$$C = (K^S * W^S) + (K^N * W^N)$$

Equation 3

K^S = cost factor of steel

W^S = weight of steel

K^N = cost factor of new material

W^N= weight of new material

The CER equation is dependent on the level of available technical data. As more data is available, a better cost relationship can be established. There are also the factors that go into the parametric cost estimating method and are essential to be considered by the estimator. The following should be considered:

- shipyard work center productivity
- stage of construction

- design complexity or design density
- economic inflation
- learning curve
- multi-ship material cost
- multi-ship engineering and planning cost
- material waste factor
- differences in procurement quantity and contract type

There are also unforeseen natural factors such as labor strikes, hurricanes, or technical issues that may require extensive rework.

3.2.5.3. Engineering Build Up Cost Estimating Model

The engineering build-up cost estimating model is conducted at the Technology Development and System Development and Demonstration phase, a much later stage than when the parametric method is used. The bottom-up method uses actual contract pricing for equipment and is the most accurate method. Labor costs are estimated based on current or anticipated shipyard labor costs. The estimator needs to cross check the final numbers with updated CERs and understand that although the final number can be precise, it is not always necessarily accurate. The Engineering build-up cost estimating takes a much longer time to perform than the parametric or analogy method and is continuously updated throughout the Production and Development stage of the life cycle. Some agree that the engineering build up model is a better forecasting model than a model used in the CER method since it uses actual cost data rather than forecasting data. But NAVSEA cannot use the engineering build up model at early stages in the estimation process.

3.2.6. Task 6. Collect Data

For NAVSEA to generate reliable cost estimation, they must obtain reliable data. Figure 8 lists 9 potential sources of data.

	Data Source	Source Type (Primary or Secondary)
1	Basic Accounting Records	Primary
2	Cost Reports	Either (Primary or Secondary)
3	Historical Databases	Either
4	Functional Specialist	Either
5	Other Organizations	Either
6	Technical Databases	Either
7	Other Information Systems	Either
8	Contracts or Contractor Estimates	Secondary
9	Cost Proposals	Secondary

Figure 8. Nine Potential Sources of Data[19]

In general NAVSEA will use primary source of data since the quality of the secondary sources can be unreliable. These nine sources of data can be categorized into three types. They are cost data, schedule data, and technical data. Cost data are generally only focused on the costs of labor, material and overhead costs. Schedule data deals with time sequence and duration for each major event over the entire lifecycle of each ship. The technical data uses parameters such as length overall, maximum beam, light ship displacement, margin, shaft horsepower, accommodations and armament to define the ship's cost. Some of this data is obtained from the private shipbuilders themselves. Because of the competitive nature of government contracts, the data released to NAVSEA from companies are business sensitive and proprietary. The Navy has developed a trust between the private companies insuring that the released data will only be used for contracting and cost estimating purposes to prepare future budget requests. NAVSEA Cost

[19] Ibid.

Engineering and Industrial Analysis Division keeps the largest and most detailed collection of cost data which includes vendor quotes, contract data and actual return cost for ships.

NAVSEA05C is not the only entity that performs cost analysis. The US coast guard, U.S. Army, and Military Sealift Command are also involved in shipbuilding in their own ways. Their own cost model and evaluation can be compared and/or interchanged for mutual benefit. In addition, other government agencies and industry trade associations such as United States Government Accountability Office or Society of Naval Architects and Marine Engineers (SNAME) often publish cost data through conferences and papers that can be used as secondary data sources.

3.2.7. Task 7. Run Model and Generate Point Estimate

This next task is to validate as best as possible the model estimate created in tasks one through six. The total cost is split according to the budget year and the model is looked at a high level to catch any obvious issues and to ensure that it “makes sense”. Next, sensitivity analysis is performed to further validate the model. Finally, the model is modified with more data (if available) and corrected from any errors discovered during the validation stage.

3.2.8. Task 8. Conduct Cost Risk Analysis and Incorporate into Estimate

Once the model is generated and validated, risk and uncertainty analysis is conducted. NAVSEA uses commercial off the shelf software to calculate risk and uncertainty. The first is Crystal Ball, a Microsoft Excel add-in and the other software is RI$K, a Department of Defense sponsored software which works together with the Automated Cost Estimating Integrated Tools (ACEIT) suite. Depending on the software basis used by the estimator, either the Microsoft

Excel add-on will be used or the ACEIT based. Crystal Ball shown in Figure 10, uses a Spearman Rank correlation and RI$K uses a Pearson Product Moment. Several research papers shows that results from either of these products are consistent and results match well with analytical results. [20] In any case, this software is a tool that gives decision makers a cost range, a probability of achieving a point estimate, and the project's cost drivers. The analysis includes the use of "S" curves, seen in Figure 9, which is the cumulative probability distribution curve that gives a confidence value for a targeted amount.

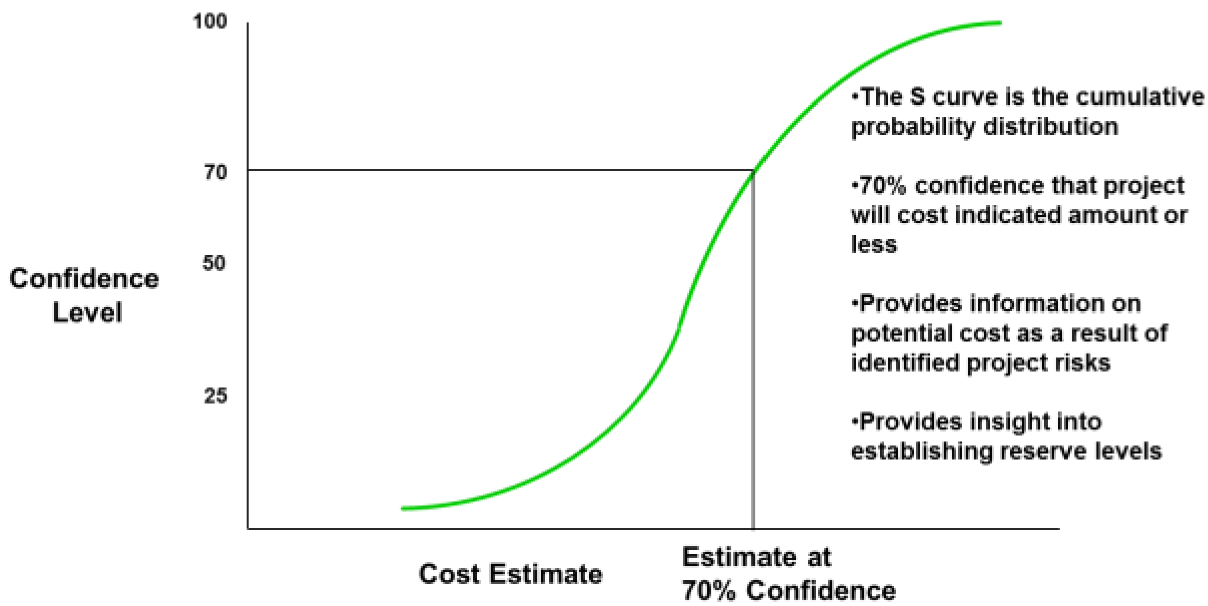

Figure 9. S-Curve[21]

[20] Hu and Smith, *Proceedings of the 2004 Crystal Ball User Conference COMPARING CRYSTAL BALL ® WITH ACEIT*.
[21] Smart, "The Portfolio Effect Reconsidered."

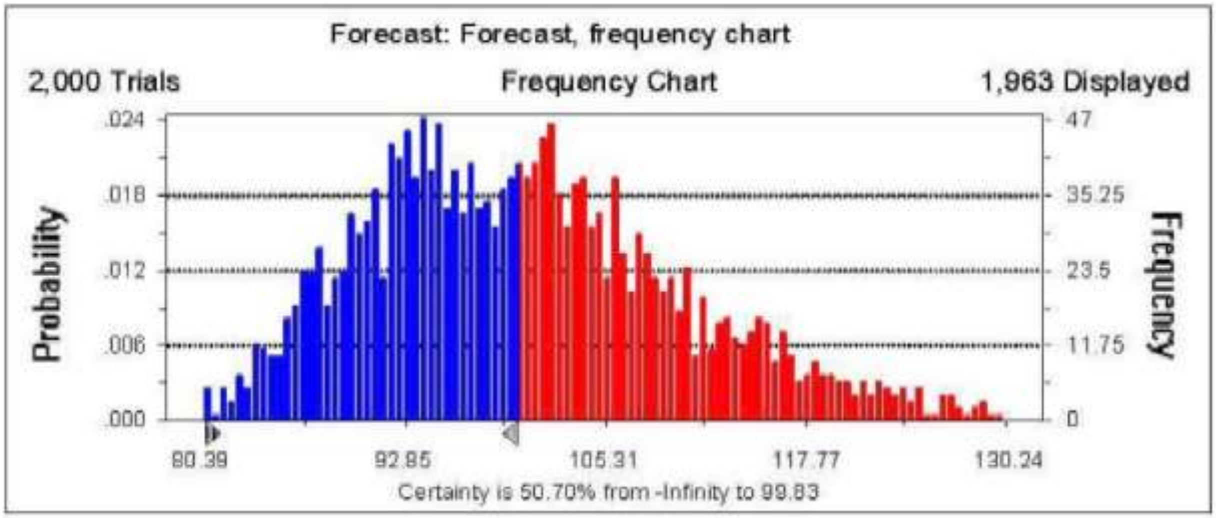

Figure 10. Crystal Ball Output (Cumulative Probability Distribution)[22]

4. Weight-Based Cost Estimation

4.1. NAVSEA's use of weight-based CER

NAVSEA's main Cost Estimating Handbook, published in 2005 is the standard for cost estimating at NAVSEA and the "foundation for the development of ship, and other ship system cost estimates."[23] In Section 4 of their manual, they state that

> "Weight is the most consistent physical property that the designer is able to provide to the ship cost estimator. Therefore, the most common parametric form employed in ship cost estimating uses weight as the technical parameter."[24]

Weight, in the past and still today is the major variable in early stage cost estimating relationship (CER). It is used as a quick method to estimate a ship cost if there is a comparable ship for comparison. This method is very much accepted within the shipbuilding industry.

[22] Deegan, "2005 NAVSEA Cost Estimation Handbook."
[23] Ibid.
[24] Ibid.

4.2. Congressional Budget Office's use of weight-based CER

For example, the Congressional Budget Office, in their annual Resource Implication of the Navy's FY 2009 Shipbuilding Plan used a historical cost-to-weight ratio of the FFG-7 frigate to estimate the cost of the lead LCS ship.

> In particular, using the lead ship of the FFG-7 Oliver Hazard Perry class frigate as an analogy, historical cost-to-weight relationships indicate that the Navy's original cost target for the LCS of $260 million in 2009 dollars (or $220 million in 2005 dollars) was optimistic. The first FFG-7 cost about $670 million in 2009 dollars to build, or about $250 million per thousand tons, including combat systems. Applying that metric to the LCS program suggests that the lead ships would cost about $600 million apiece, including the cost of one mission module. Thus, in this case, the use of a historical cost-to-weight relationship produces an estimate that is less than the actual costs of the first LCSs to date but substantially more than the Navy's original estimate.[25]

This $600 million estimate for the lead ship in 2008 was actually much closer to the budgeted cost of LCS-1 in 2013, which came out to $670.4 million.[26] A simple cost-to-weight ratio performed by CBO ended up producing much better estimates than the low estimate proposed by the Navy of $220 million.

In addition, in a report in 2005 by the CBO, four basic approaches for arriving at lower-cost designs for Navy ships were proposed. They were (1) Reducing ship size, (2) Shifting from nuclear to conventional propulsion, (3) Shifting from hull built to military survivability standards to a hull built to commercial-ship survivability standards, and (4) Using a common hull design for multiple ship classes. The first cost reducing method of reducing ship size was based on a weight-based cost relationship. But as mentioned before, reducing ship size will potentially increase complexity and drive costs.

[25] O'Rourke, "Navy Littoral Combat Ship (LCS) Program: Background and Issues for Congress."
[26] Ibid.

4.3. RAND's use of weight-based CER

Other major studies use weight as a predictor for cost estimation. The federally funded 2006 study by RAND National Defense Research Institute uses light ship weight as a predictor for cost using regression analysis.[27]

4.4. MIT Cost Model's use of weight-based CER

The MIT 2N Naval Architecture program uses a simplified weight based cost model for academic purposes. This model, seen in Figure 11 and Figure 12 was created in 1975 (and updated several times) from a Math model used to determine cost of Navy frigates. The original concept was never intended to serve as an accurate cost estimator but gave rough cost estimates within certain parameters of weight and type of combatant. Since then, the excel worksheet has been updated for ships outside frigates and has been used by Naval Architecture students to provide a rough estimate for cost. It takes inputs of SWBS group weights and output costs. It also has been modified to calculate life cycle costs based on inputs such as manning and number of ships in class.

[27] Arena et al., "Why Has the Cost of Navy Ships Risen?".

Inputs		
Weights	Long Ton	in Mtons
SWBS 100	1005.84	990.00
SWBS 200	55.17	54.30
SWBS 300	102.11	100.50
SWBS 400	132.69	130.60
SWBS 500	340.77	335.40
SWBS 600	231.14	227.50
SWBS 700	28.24	27.80
Margin	237.34	233.60
Loads	548.44	539.80

Change Orders (Lead)	10%
Change Orders (Follow)	5%
Profit	10%
Lead Ship T unit =	1
Follow Ship T Unit =	5

Learning Curve %	92%
Life Cycle Cost Factor (from table)	9.86

GRP 1	HULL STEEL
GRP 2	PROPULSION
GRP 3	ELECTRIC
GRP 4	COMMAND
GRP 5	AUXILIARY
GRP 6	OUTFIT
GRP 7	ARMAMENT

sustn speed condition used

29075 bhp each engine

116300 bhp

DDA

INPUTS FOR CALCULATING LIFE CYCLE COST	
Total Brake Horsepower (hp)	2799.67275
SWBS 420-439 Weights (LT)	18.288
Average Deck Height (ft)	10.494

CREW/MANNING	
Officer	14
CPO	13
Enlisted	86
	113
Number of Ships in Class	12
Ship Service Life (years)	30
Initial Operational Capability (year)	2020
Production Rate (ships/year)	2

Inflation	
Base Year	2012
Average Inflation Rate	3.9
Number of Operating Hrs Per Year	3000
Fuel Cost ($/gal)	3.00
Fuel Consumption Rate (lton/hr)	6.4

Figure 11. Example of a MIT Cost Model Input

P5 Cost Output	FY05 $k		FY05 $k	
	Lead		Follow	
Plan Costs	$	56,173.88	$	12,939
Basic Construction	$	187,246	$	161,734
Change Orders	$	18,725	$	8,087
Electronics	$	91,130	$	78,714
Hull, Mech, Electrical	$	10,862	$	9,382
Other Costs	$	8,609	$	7,436
Ordnance	$	185,887	$	160,560
Total	**$**	**558,633**	**$**	**438,850**

	LCC	
Total Ship R&D Cost	$	511,144,504
Total Investment Cost	$	5,918,869,091
Total Operating and Support Cost	$	13,787,167,703
Residual Value	$	(298,814,746)
TOTAL PROGRAM LIFE CYCLE COST	$	19,918,366,552

Figure 12. Example of a MIT Cost Model Output

Unfortunately, naval architecture students at MIT do not have any other means of cost estimation in their ship conversion and design classes and this weight-based excel sheet is commonly used.

4.5. Disadvantages of Weight Based Cost Estimation

Cost estimators at NAVSEA know that weight-based cost estimating is outdated and should be updated based on changes and advances in ship design, construction and complexity. Yet the practice of weight-based cost estimation is still prevalent in research and government.

One of the reasons why weight based cost modeling is flawed is that it causes the designer to optimize the ship cost based on weight and size, inclining ships to be smaller. And with the recent trend of adding more capabilities on fewer platforms, ships have become denser. A dense ship is more complicated and requires more man-hour labor for construction. Figure 13 clearly shows the relationship between the denseness of US naval ships with normalized ship production hours. As ships become denser, more production hours are required to build them.[28]

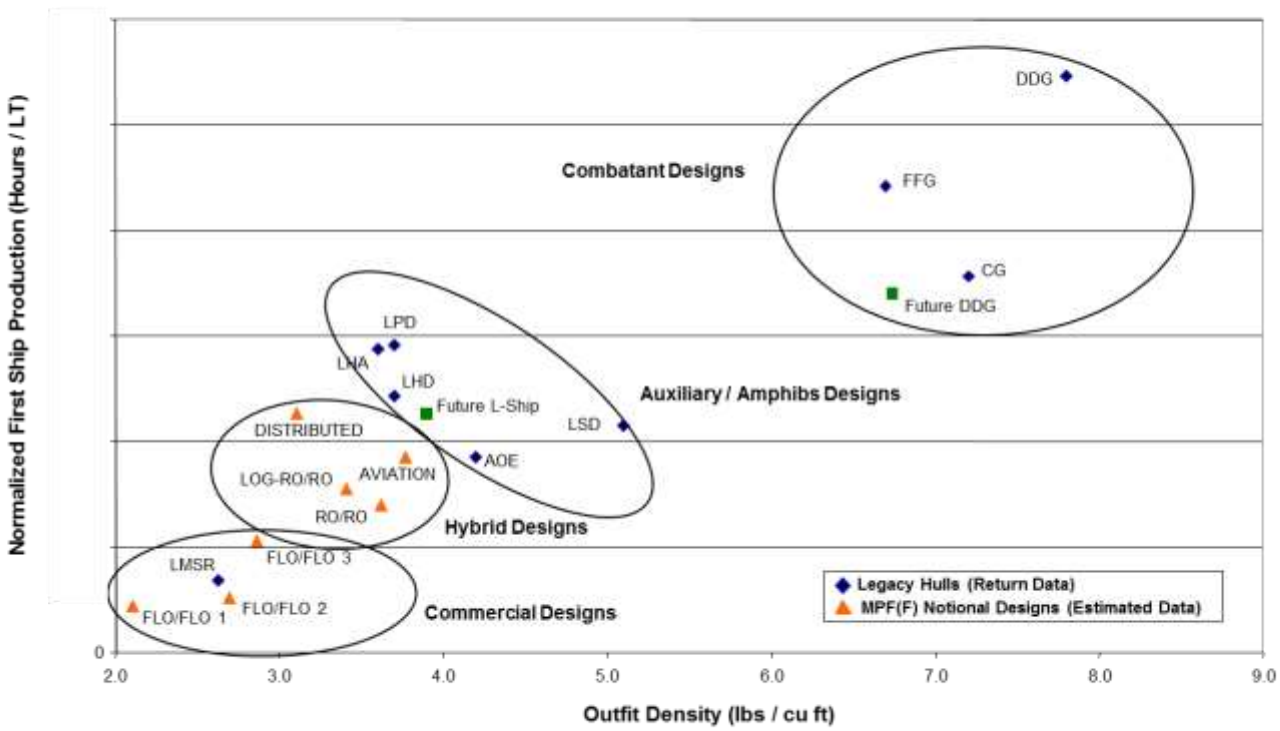

Figure 13. Ship Density vs. Production Hours[29]

As you can see in the figure 13, a DDG-51 class ship is the densest surface combatant and results in the highest normalized production hours. As ships increase in density, it becomes harder for workers to obtain access to compartments, making construction more difficult and requiring more man-hours.

The general idea that larger ships cost more money needs clarification because it can be misunderstood. It is true that larger ships in general cost more money than smaller ships, a 10,000 ton destroyer will cost more than a 4,000 ton frigate, but for a given ship with the same

[28] Snyder, "NAVSEA's Latest Advances in Estimating Ship Costs."
[29] Ibid.

capability, creating a larger hull to better accommodate equipment will reduce density and complexity. Some naval ship designs in the past have not taken into account the relationship between size, density and cost. In fact, some NAVSEA engineers, through conversation, admit that the DDG-51 hull could have been designed a bit larger for the later flights updates.

Increased density and complexity can drive ship costs for a given ship. A great example is seen in the difference between the Korean, Japanese and American AEGIS destroyers explained in section 4.6. It is often stated that air is free and steel is cheap. And that the relative cost of steel is low compared to the increased cost of producing ships that are dense and complex. In general, designing larger, roomier ships with producibility in mind will require less labor hours for construction than a smaller, denser ship.

Another example of when weight-based decision making would not necessarily be cost-effective would be generator selection between diesel and gas turbine (GT). Diesel generator's weight to power ratio is significantly higher than gas turbine generators. If a weight optimization model was used to select generator type for naval ships, then gas turbine generators would have an advantage over diesel generators. But these two types of generators have different performance characteristics at different operating speeds. GTs tend to have a much lower fuel efficiency at lower speeds while diesel generators tend to have more stable fuel efficiencies at varying speeds. Because surface combatants tend to operate the majority of time in slower cruising speeds, it would be more cost- and fuel-efficient to select engines that are optimized for ship's speed profile, rather than weight.[30]

[30] Webster et al., "Alternative Propulsion Methods for Surface Combatants and Amphibious Warfare Ships."

4.6. Japanese and Korean AEGIS ship comparison

The Arleigh Burke (DDG-51) Class AEGIS Destroyer is the densest surface combatant ship that exists today. A 2005 DoD-sponsored study found that the current DDG-51 design is about 50% more dense and complex than any modern international destroyer. Density is a measure of all internal equipment, hardware, piping, etc., per internal volume.[31]

The Japanese and Korean national commercial shipbuilding programs are vast enterprises, holding over 47% of the world's market share in 2012. Details are found in Appendix F. This expertise has no-doubt migrated into an efficient naval shipbuilding program. In 1990, the Japanese Self-Defense force built the Kongo class guided missile destroyer (DDG-173) inspired after the US Arleigh Burke Destroyer design. It shared the same characteristics including the AEGIS radar system with SPY-1 radar, and similar sensors and weapon systems. The South Korean Navy, in 2007, built the KDX-III Sejong the Great class guided missile destroyer, (DDG-991) again in the same design as the Arleigh Burke, sharing the AEGIS and SPY-1 radar and weapons system and a host of similar attributes and equipment. A side-by-side comparison of the three ships in Figure 14 shows the obvious similarities between the ships.

The Japanese and Korean shipbuilders took the already dense design of the Arleigh Burke class and built their own version slightly longer and wider. They built their ship with producibility in mind increasing the length by an average of 12% and the width by an average of 5%. Figure 14 and 15 shows the comparisons between the three ships.

[31] United States Government Accountability Office, "ARLEIGH BURKE DESTROYERS. Additional Analysis and Oversight Required to Support the Navy's Future Surface Combatant Plans."

Figure 14. Top – US Arleigh Burke Destroyer (DDG-80)
Middle – South Korean KDX-III Destroyer (DDG-991)
Bottom – Japanese Kongo Class Destroyer (DDG 174)

Comparison of US, South Korean, and Japanese design				
	Length (ft)	Width (ft)	Fully Loaded Displacement (LT)	Density (lbs/ft^3)
Arleigh Burke Class	509	66	9,600	7.81
KDX-III Class	539 (+5.9%)	70 (+6%)	10,000	7.24*
Kongo Class	598 (+17.5%)	69 (+4.5%)	10,000	6.62*

*extrapolated

Figure 15. Comparison of three similar AEGIS capable Destroyers

Figure 15 shows that the Korean KDX-III ship and the Japanese Kongo ship were built 30ft and 89ft longer than the US Arleigh Burke ship, most likely to reduce density and complexity. The resulting density (lbs/ft^3) of the KDX-III and Kongo class ships are 7.24 and 6.62 respectively, which is significantly lower than Arleigh Burke class of 7.81, the highest of any warship in the world. The density of the Arleigh Burke class was obtained from a 2007 SNAME-ASNE joint conference presentation and will be discussed later in this paper.[32] The density of the Korean and Japanese AEGIS ships were calculated from extrapolating the density of the Arleigh Burke ship, assuming similar internal outfitting and hull shape. All equipment within the ship is assumed to remain constant and the only change is the length and width of the hull.

4.6.1. Cost of South Korean Sejong the Great KDX-III DDG-991

The South Korean Joint Chief of Staff on December 2013 announced their plans to build three more AEGIS destroyers at a total cost of US $3.8 billion ($1.27 billion per unit)[33]. Compared with the unit cost of US Arleigh Burke Destroyer of which is approximately $1.94

[32] Snyder, "NAVSEA's Latest Advances in Estimating Ship Costs."
[33] Kim, "(EALD) S. Korea to Build Three More Aegis Destroyers."

billion (average of cost of last four destroyers), the KDX-III is about 65% of the cost of the latest Arleigh Burke destroyer.

Cost in $ million	
DDG-113	2234.4
DDG-114	1749.7
DDG-115	1749.7
DDG-116	2028.7

Average Cost	1940.6

Figure 16. Cost of last four US Arleigh Burke destroyers[34]

4.6.2. Cost of Japanese Kongo Class DDG-173

The Japanese Kongo Class ship is 89 feet longer and 3 feet wider. Although we do not have an estimate of the cost, we know that design and construction man-hours is observed to be significantly less than the Arleigh Burke program based on a benchmarking report done in 1993 by NAVSEA.[35]

5. Methodology

5.1. General Approach

This study was intended to explore whether other variables such as outfit density and power density will improve the cost estimating relationship, as compared with weight alone. The following procedure was developed and followed:

1. Determined interest and need of new CER and feasibility of research
    a. Interviews

[34] O'Rourke, "Navy DDG-51 and DDG-1000 Destroyer Programs: Background and Issues for Congress."
[35] Summers, "Japanese Aegis Destroyer."

    b. Literature Review
2. Determined scope of research and data feasibility
    a. NAVSEA contacts
3. Collected data
    a. Obtained LSW, Cost, Electric Power, SHP, crew size, number of armaments.
    b. Open source data
        i. Naval Vessels Registry www.nvr.navy.mil
        ii. Federation of American Scientist www.fas.org
        iii. Navy Finance www.finance.hq.navy.mil
        iv. Internet web search
    c. NAVSEA obtained data
        i. Cost data obtained from NAVSEA 05C3
    d. Normalized data
        i. Accounted for inflation using DoD Joint Inflation Calculator for Shipbuilding and Conversion, Navy.
        ii. Accounted for learning curve, used 9^{th} ship in class
    e. Confirmed data from other sources
4. Regression analysis and best fit
5. Identified trends and additional observations
6. Provided conclusion and recommendations for future analysis

5.2. Ships selected for Analysis

To obtain the best regression model and CER, the highest number of data points were sought out. Ships were grouped according to class and were selected only if density information were available. This density data was the limiting factor for the number of data points. Because density data was not released by NAVSEA and non-disclosure agreements with shipyards were not signed, only publically-releasable information could be used. Density information was obtained from a chart in a presentation presented at a joint SNAME-ASNE conference in 2007.[36]

Below are the ships used for analysis:

USS Leahy (CG-16) Class Cruiser

Launched:	1959
Displacement:	8281 LT
Length:	533 ft
Beam:	55 ft
Year built:	1959

USS Belknap (CG-26) Class Cruiser

Launched:	1962
Displacement:	8957 LT
Length:	547 ft
Beam:	55 ft
Year Built:	1962

USS Ticonderoga (CG-47) Class Cruiser

Launched:	1988
Displacement:	9600 LT
Length:	567 ft
Beam:	55 ft
Year Built:	1988

USS Spruance (DD-963) Class Destroyer

Launched:	1970
Displacement:	8040 LT
Length:	529 ft
Beam:	55 ft
Year Built:	1970

USS Arleigh Burke (DD-51) Class Destroyer

Launched:	1991
Displacement:	8900 LT
Length:	505 ft
Beam:	66 ft
Year Built:	1991

[36] Snyder, "NAVSEA's Latest Advances in Estimating Ship Costs."

USS Oliver Hazard Perry (FFG-7) Class Frigate

Launched:	1983
Displacement:	4100 LT
Length:	445 ft
Beam:	45 ft
Year Built:	1983

USS Zumwalt (DDG-1000) Class Destroyer

Launched:	2013
Displacement:	14564 LT
Length:	600 ft
Beam:	81 ft
Year Built:	2009

USS Tarawa (LHA-1) Amphibious Class

Launched:	1971
Displacement:	38900 LT
Length:	820 ft
Beam:	106 ft
Year Built:	1971

USS Wasp (LHD-1) Amphibious Class

Launched:	1984
Displacement:	40532 LT
Length:	844 ft
Beam:	106 ft
Year Built:	1989

USS San Antonio (LPD-17) Amphibious Class

Launched:	1996
Displacement:	25000 LT
Length:	208 ft
Beam:	32 ft
Year Built:	1996

USNS Lewis and Clark (T-AKE-1) Cargo Class

Launched:	2006
Displacement:	41000 LT
Length:	689 ft
Beam:	105 ft
Year Built:	2010

USS Harpers Ferry (LSD-49) Class

Launched:	1993
Displacement:	16601 LT
Length:	610 ft
Beam:	84 ft
Year Built:	1993

USS Whidbey Island (LSD-41) Class

Launched: 1985
Displacement: 16360 LT
Length: 610 ft
Beam: 84 ft
Year Built: 1985

USNS Supply (AOE-6) Class

Launched: 1987
Displacement: 4960 LT
Length: 755 ft
Beam: 107 ft
Year Built: 1987

5.3. Data

The data used to determine a new Cost Estimating Relationship includes 1) Final "end unit cost" which includes all Government-furnished equipment and Contractor-furnished equipment but not research and development costs, 2) Light Ship Weight, 3) Total Electrical Power Generation, 4) Maximum Shaft Horsepower generated, and 5) Outfit Density.

5.4. Cost data

Cost data was obtained from both NAVSEA05C and from the Navy Finance website. NAVSEA05C released cost data from their Historical Cost of Ships database which contains SCN end-cost data broken out by category. The database contained the cost of every ship in a class broken down by basic construction, construction plans, change orders, electronics, HM&E, Propulsion, Other cost, Ordnance, and Escalation. The summation of all these components made up the end-cost value, which is the procurement cost. The procurement cost for the DDG-1000 was unavailable so cost information was obtained from the Congressional Research Service and normalized according to methods explained in the following chapters.[37] All other cost data were obtained from NAVSEA05C's Historical Cost of Ships database.

5.4.1. Learning Curve

For a valid cost comparison between ships of different classes and CER, the learning curve was taken into account. A learning curve is defined by the following formula:

$$T_n = T_1 n^{\frac{\ln(S)}{\ln(2)}}$$

Where:

T_n is the cost for the nth unit

T_1 is the cost for the first unit

n is the number of units produced

S is the "learning percentage" expressed as a decimal

Typical learning percentages are shown in figure 17.

Manufacturing Activity	Typical Slope %
Electronics	90-95
Machining	90-95
Electrical	75-85
Welding	88-92

Figure 17. Typical learning Curve values[38]

[37] O'Rourke, "Navy DDG-51 and DDG-1000 Destroyer Programs: Background and Issues for Congress," 100.
[38] Stump, "All About Learning Curves."

For shipbuilding, the typical learning curve is between 80% and 85%. As operations become more labor intensive, learning rate increases. Operations that are fully automated have almost no learning, while operations that are entirely manual labor tends to have learning rates around 70%.[39] Figure 18 shows learning curves for 90%, 85% and 80% learning.

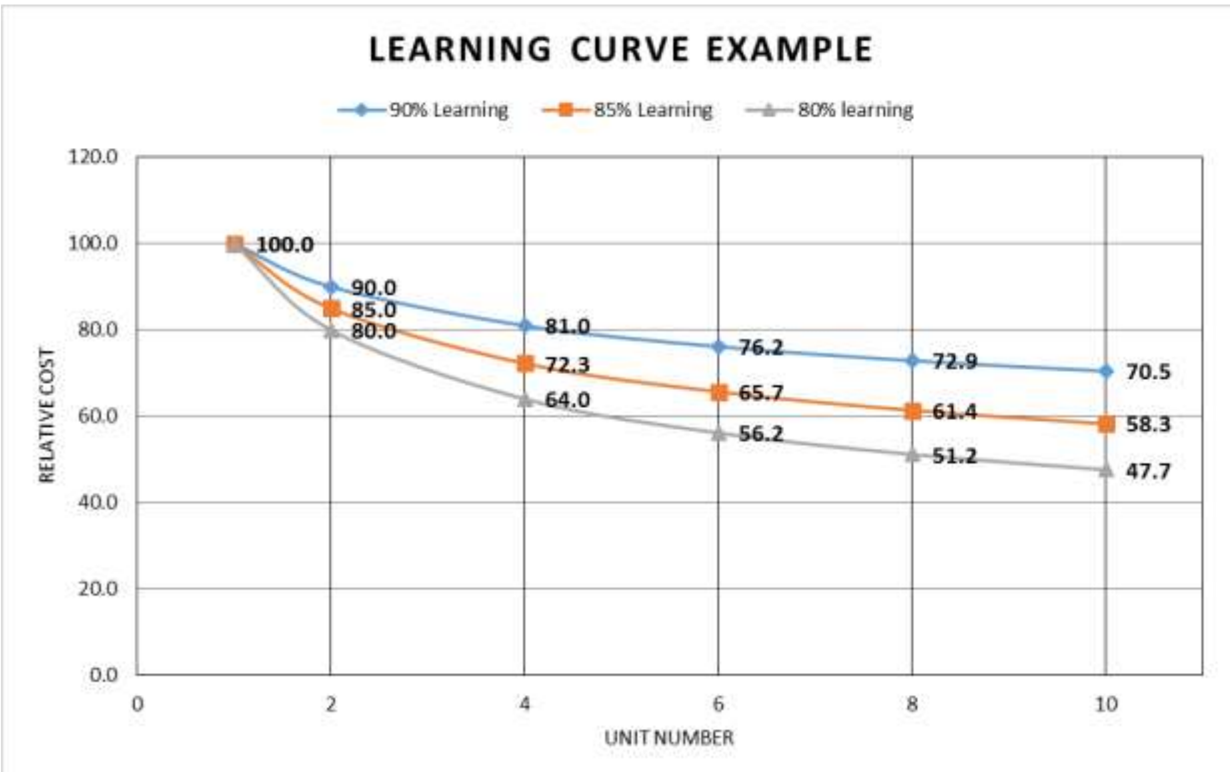

Figure 18. Learning Curve example

For data analysis, the cost of each ship was separated depending on in which shipyard it was built. Then the cost of the 9th ship in that shipyard was selected because the learning curve had sufficiently leveled out by the 9th ship in the class with price being relatively constant. If there were no 9th ship built, a learning curve was fitted based on available data. For example, in Figure 19, only cost data for the first three CG-16's built at Bath Iron Works were available in red. An 80% learning curve in blue was fitted to obtain the theoretical 9th ship in that class for a

[39] Ibid.

given shipyard. This method was done for several other ship classes and the observed learning curve for these ships ranged from 78% to 97%.

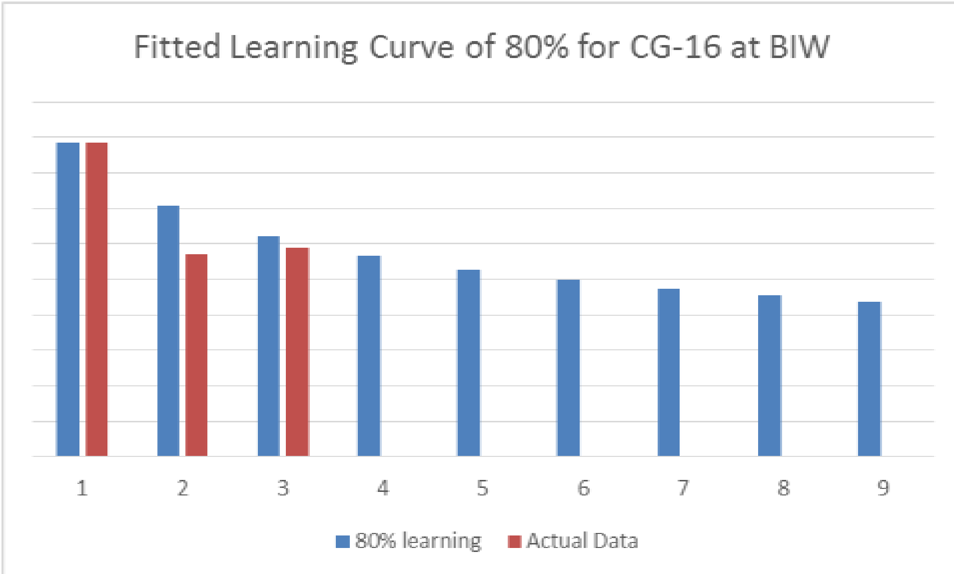

Figure 19. Fitting learning Curve of 80% for CG-16 at BIW

5.4.2. Inflation Normalization

The end-cost price from the NAVSEA database is recorded in then-year (TY) dollars. To normalize the values for inflation, the DoD Inflation Table for Navy Shipbuilding and Conversion was used to convert to 2014 dollars. The inflation table accounts for actual yearly inflation rates since 1970. For the two ships that were built before 1970, CG-16 and CG-26 a standard US Government CPI index was used. A comparison between the DoD inflation table and US CPI index inflation table did not show a remarkable difference in results.

5.5. Other data

Light ship weight, electric power generation, crew size, number of armaments, length and beam were obtained from open source webpages such as Naval Vessels Register and Federation of American Scientists. Because of the sensitivity with competitive cost information, shipbuilders and NAVSEA were very hesitant to give out information. Normally, this sensitivity makes it difficult to obtain actual data from NAVSEA. We were able to obtain cost information from NAVSEA05C but other data used in this paper are strictly from open sources on the internet and naval society conference presentations. To use other detailed data from NAVSEA, one would have to sign a non-disclosure agreement and the material could not be published without specific permission.

5.5.1. Calculating Density

5.5.1.1. Internal Outfit density

The most challenging and important task of this thesis was to discover, define and relate variables other than weight to explain the changes in ship cost. A variable suggested by NAVSEA05C was internal outfit density. As equipment is closely packed, the ship becomes denser and outfit density could be a good indicator to ship costs.

Outfit Density is defined as:

$$Outfit\ Density = \frac{weight\ of\ all\ interior\ systems\ and\ equipment}{volume\ of\ interior}$$

This can be approximated in terms of the Navy's SWBS group breakdown in the following way.

$$Outfit\ Density = \frac{\sum Weight\ of\ SWBS\ Groups\ 200 - 700}{Total\ ship\ volume}$$

Normally, the weights of SWBS Groups 200-700 and the total ship volume can be pulled from Navy's Advanced Ship and Submarine Evaluation Tool (ASSET) program, but this was unavailable for this thesis so outfit density was obtained from a 2007 SNAME-ASNE Joint Conference presentation by Mr. Jim Snyder of NAVSEA05C.

5.5.1.2. Electric Power density

Electrical Power density can be a good measure of ship complexity since it is an indication of how many electrical systems are on a ship given size. The concept of power density was explained very clearly in the 2006 study conducted by RAND National Defense Research Institute, "Why Has the Cost of Navy Ships Risen?"[40]

In the paper, electrical power density is defined as follows:

$$Electric\ Power\ Density = \frac{Total\ Electric\ Power\ Generation}{Light\ Ship\ Weight}$$

But electric power density may not be a perfect measure because as technology evolves and circuits become more efficient, less power will be required for the same computation power. Nevertheless, the 2006 RAND study in Figure 20 shows an increase in power density for surface ships from 1970-2000 and proposes that this 40% increase in power density may explain the lack of significant increase in shipyard productivity.

[40] Arena et al., "Why Has the Cost of Navy Ships Risen?".

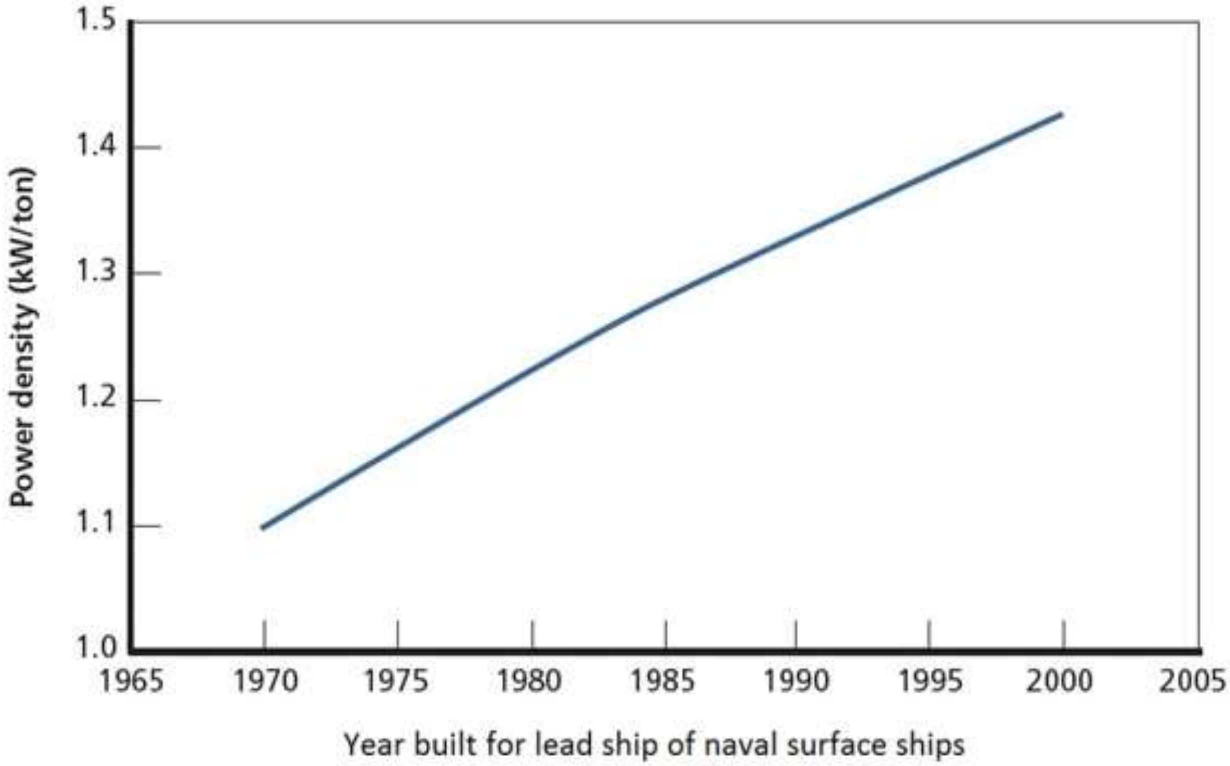

Figure 20. Increase in Density for Surface Ships from 1970-2000[41]

5.5.1.3 Ship Permeability

Ship permeability could also be a very good and direct measure of ship complexity. Permeability of a ship (by compartment) is calculated for reasons of damage stability calculations. Permeability percentage indicates how much sea water could potentially fill a space in case of flooding of the compartment, with the rest of the compartment occupied with equipment and other machinery. Permeability is required for the naval architect to determine how many water tight bulkheads are required to be installed so that the ship will stay afloat with a given number of compartments flooded.

[41] Arena et al., "Why Has the Cost of Navy Ships Risen?".

Permeability can be very useful to measure ship complexity as compared to internal outfit density since it is totally independent of weight and measures the air volume available within the ship. One downside of permeability is that it does not distinguish between cargo stores or permanently-installed equipment. Although this research paper does not use permeability data as a potential variable for CER, a 2008 study done at the Naval Post Graduate School used permeability data as a surrogate for complexity in submarine cost estimation.[42]

6. Analysis

The following variables were regressed against total cost:

- Light Ship Weight (LT)
- Outfit Density (lbs/ft^3)
- Electric Generation (MW)
- Electric Power Density (KW/LT)
- Shaft Horsepower (MW)
- *SurfCombat (1/0)*

Light ship weight, expressed in long tons (LT) is typically used rather than full load displacement and is a better indicator of ship structure since it ignores any variable weights such as fuel, cargo, stores, and crew. Outfit density and Electric Power Density were defined previously. Electric Generation is the total power generated onboard for electrical purposes measured in MW. The *SurfCombat* is a dummy binary variable that indicates “1” if a ship is a Cruiser, Destroyer or Frigate, and “0” if vessel is not. The idea of using a dummy variable to

[42] Grant, “Density as a Cost Driver in Naval Submarine Design and Procurement.”

account for the difference in major ship classes was obtained by observations of the dataset and from the 2006 RAND Study.[43]

For the T-AKE class ship, exact electrical generation values were unknown since they utilize an Integrated Power System (IPS). Although a value for installed electrical power can be estimated by taking the difference between total installed power and the ratings of the propulsion motors, this value was not included in the dataset because could not be confirmed. The DDG-1000 class ship also uses IPS, but a value of electric power required was found in an open source document.[44] The electric power generation rating for the CG-16 class and CG-26 class was unknown because they use steam power for electrical generation. The MW rating for these ships could not be found on open source.

[43] Arena et al., "Why Has the Cost of Navy Ships Risen?".
[44] Naval Sea Systems, "US NAVY REPORT ALTERNATIVE PROPULSION METHODS FOR SURFACE COMBATANTS AND AMPHIBIOUS WARFARE SHIPS."

7. Results

A dataset of 16 ships was analyzed using statistical analysis.

7.1. Cost vs. Light Ship weight

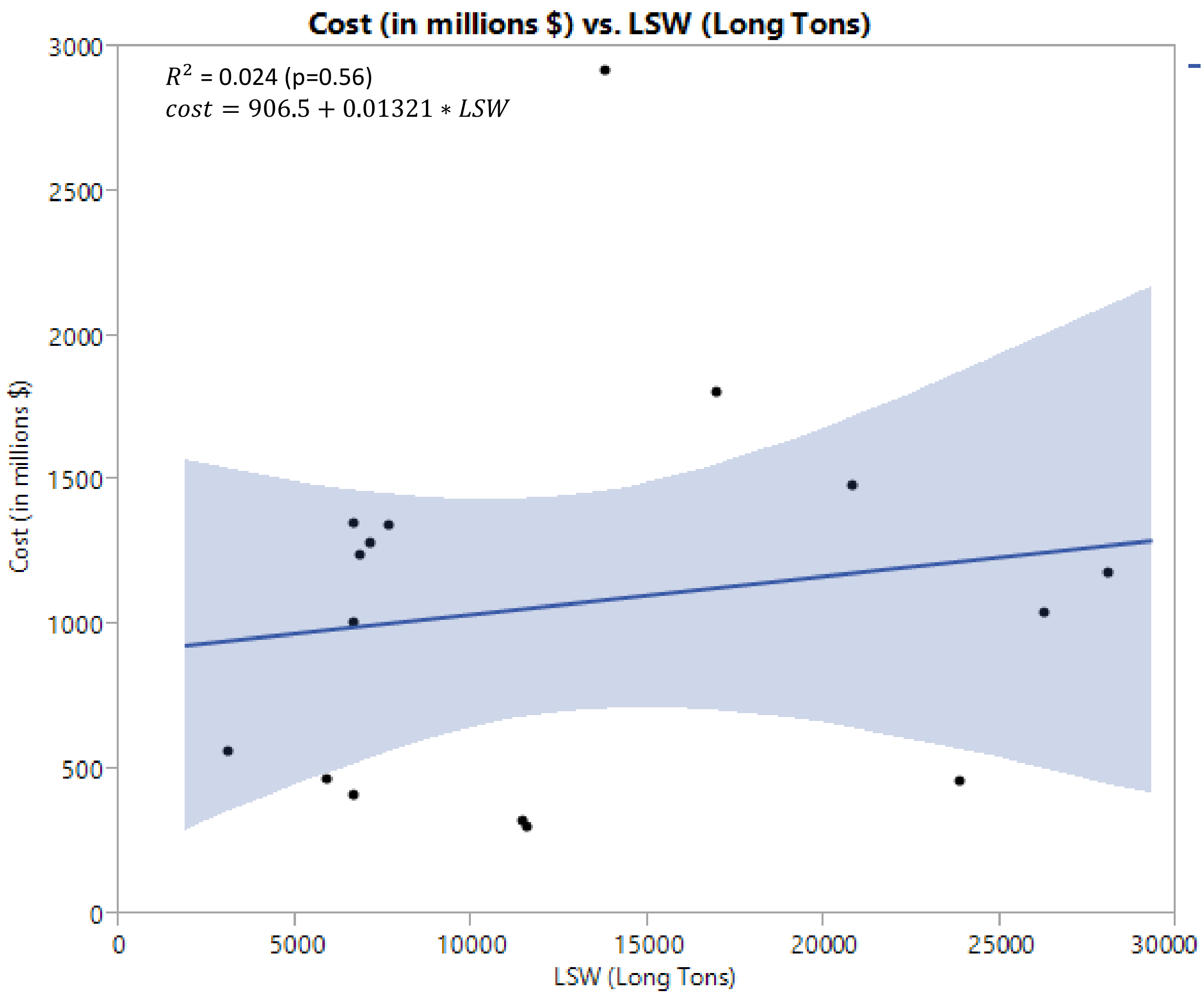

Figure 21. Cost vs. Light Ship Weight

Figure 21 shows light ship weight vs. cost. This was analyzed to evaluate the validity of a purely weight-based cost estimation. From the data set collected, we observe a very poor relationship between light ship weight and cost, with the regression model failing the null-hypothesis test with a p-value of 0.56. Even a simple visual observation shows an obvious lack of relationship between cost and weight.

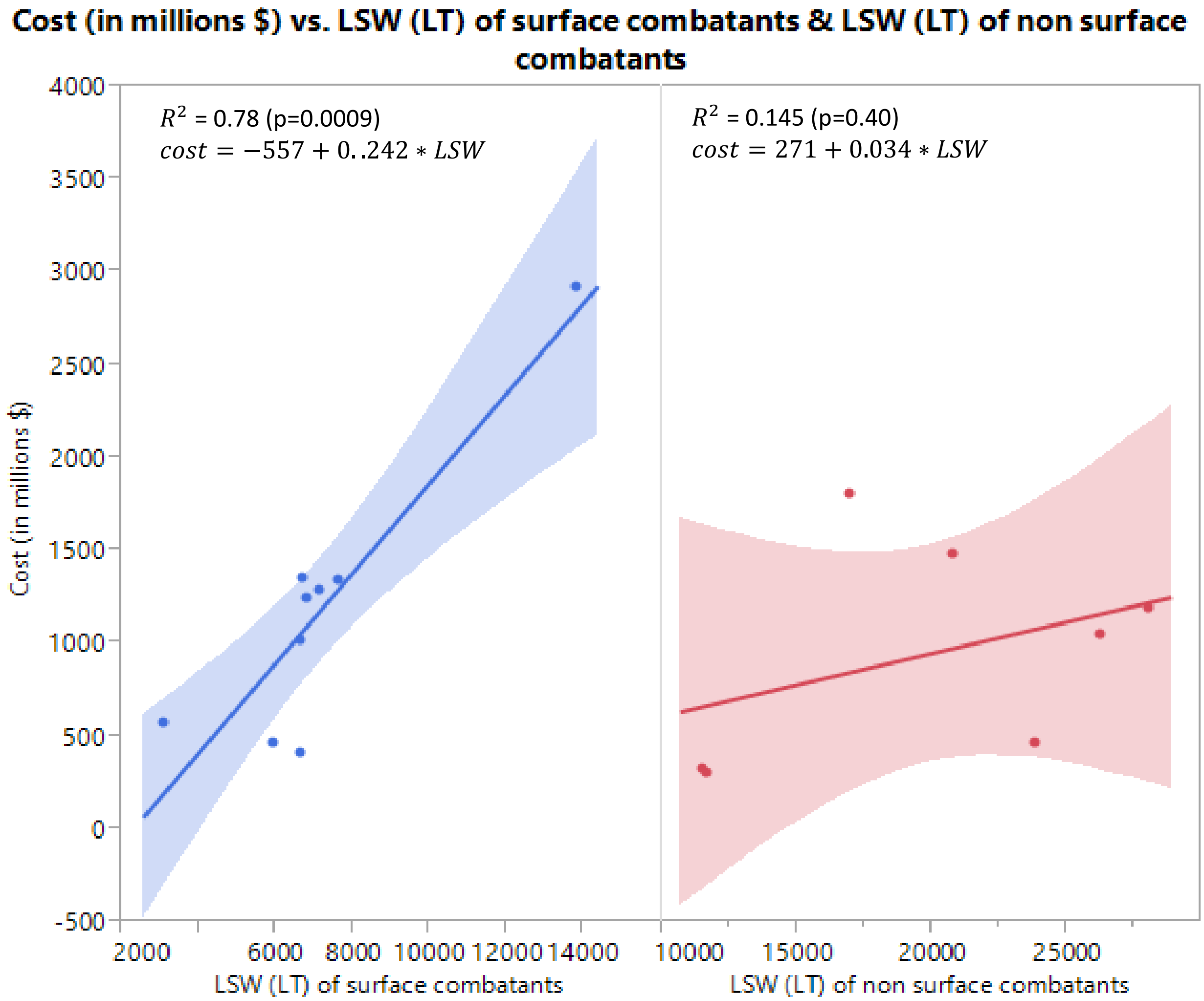

Figure 22. Cost split between Surface Combatant and non-surface combatant

Figure 22 splits the light ship weight dataset between surface combatants and non-surface combatants. At first glance, when the data is split a better regression model is observed for the surface combatant group and could potentially show a relationship between weight and cost. But this regression is heavily skewed by the expensive and heavy DDG-1000. The regression shows a R^2 value of 0.78 and p-value of 0.0009, and indicates a positive relationship between light ship weight and cost for surface combatants. But if the DDG-1000 is considered an outlier, and not included in the surface combatant regression, we would get a R^2 value of 0.34 and p-value of 0.1265 which means this regression model is not useful for predicting cost. This is important because it shows that the regression model for surface combatants is only valid because of the influence of the DDG-1000. The regression model on the right between LSW for non-surface combatants and cost has an F statistic p-value of 0.40 which means that this regression model is also not useful for predicting cost. Overall, there is a very poor relationship between cost and weight, even when the dataset is split between combatants and non-combatant ships. The full regression analysis is found in Appendix B.

7.1.1 Non-linear Transform

Residual plots were graphed to determine if there existed some uniform distribution that called for a non-linear transformation. Figure 23 shows residual plots for electric power generation and electric power density. These two residual plots show higher variations as x-value increases. Several different non-linear transforms were attempted and a log-log transform was used to help remove uniform distributions in the data set and to improve the statistical analysis. A natural log plot was used for all further regression analysis.

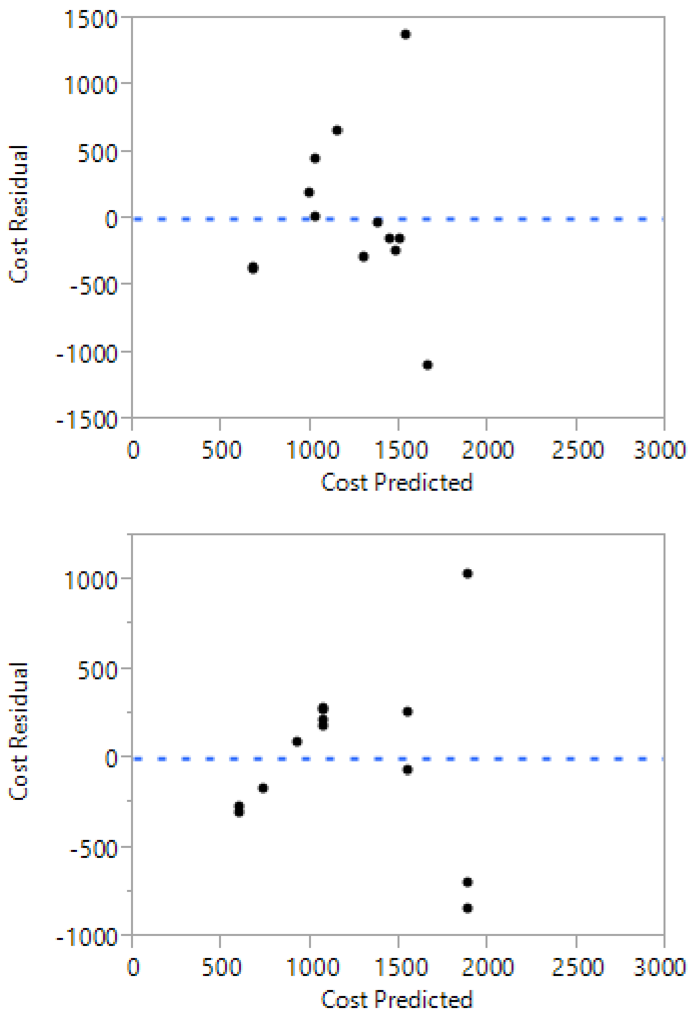

Figure 23. Residual plots for Electric Power Density (above) and Electric Power (below)

7.2 Combination Model matrix

7.2.1 Correlations

Tables below in Figure 24, were created to assess how correlated each variable was to each another, since highly correlated variables would present problems in multivariate models.

Correlations

	lnLSW	lnOutfitDensity	lnElectrical	lnElec Density	lnSHP
lnLSW	1.0000	-0.8332	0.5334	-0.5390	-0.1301
lnOutfitDensity	-0.8332	1.0000	-0.2332	0.6594	0.5451
lnElectrical	0.5334	-0.2332	1.0000	0.4249	0.5309
lnElec Density	-0.5390	0.6594	0.4249	1.0000	0.6679
lnSHP	-0.1301	0.5451	0.5309	0.6679	1.0000

The correlations are estimated by REML method.

Variable	by Variable	Correlation	Count	Lower 95%	Upper 95%	Signif Prob
lnOutfitDensity	lnLSW	-0.8130	13	-0.9420	-0.4746	0.0007*
lnElectrical	lnLSW	0.5895	13	0.0571	0.8609	0.0340*
lnElectrical	lnOutfitDensity	-0.2097	12	-0.6994	0.4141	0.5131
lnElec Density	lnLSW	-0.4537	13	-0.8037	0.1298	0.1195
lnElec Density	lnOutfitDensity	0.6359	12	0.0975	0.8863	0.0263*
lnElec Density	lnElectrical	0.4524	13	-0.1313	0.8032	0.1206
lnSHP	lnLSW	-0.1301	16	-0.5879	0.3908	0.6311
lnSHP	lnOutfitDensity	0.5175	13	-0.0468	0.8314	0.0701
lnSHP	lnElectrical	0.5936	13	0.0633	0.8625	0.0325*
lnSHP	lnElec Density	0.6550	13	0.1628	0.8862	0.0151*

Figure 24. Correlation Matrix Tables

The highlighted rows indicate variables that are correlated. The un-highlighted rows indicate variables not correlated with each other. Correlated variables such as outfit density and light ship weight should not paired together in a regression model to prevent endogeneity.

7.2.2. Combination Models

Various combinations of the five variables and dummy variable, SurfCombat was evaluated to see which model would best explain the variations in cost. Figure 25 and Figure 26 summarizes the results of the combinations of variables.

Combination Models										
	1	2	3	4	5	6	7	8	9	10
R^2 Value	0.038	0.29	0.06	0.13	0.74	0.85	0.52	0.646	0.36	0.31
F Test	0.5615 (.46)	4.123 (.04)	.707 (.418)	1.9 (.2)	32.14 (.0001)	35.2 (.0001)	11.7 (.0057)	11.93 (.0022)	33.1 (.0001)	27.2 (.0002)
1. ln*LSW*	11.9 0.46	1.02 0.016								
2. ln*Outfit Density*			0.476 0.418	-2.377 0.2						
3. ln*Electrical*					0.8 0.0001	0.82 0.0001				
4. ln*Elec Density*							0.73 0.0057	1.3 0.001		
5. ln*SHP*									0.87 0.001	1.09 0.01
6. *SurfCombat*		1.26 0.017		1.87 0.115		0.414 0.009		-0.811 0.03		-0.32 0.335

coefficient
p-value

Figure 25. Combination Model Results

From the first group of 10 variable models, the best statistical fit was model 6.

$$\boldsymbol{lnCost_9 = 0.820 * lnElectrical + 11.915}$$ **Model (6)**

It had the highest R^2 value of 0.85, highest F-value of 35.2 and a p-value of .0001. In general, shaft horsepower, electric density, and electric power are statistically significant in isolation, while light ship weight and outfit density has no statistical significance to the regression. It is surprising to see that outfit density has no explanation power in the regression analysis because Figure 13 in Section 4.5 shows a clear relationships between outfit density and normalized ship production hours. As a result, outfit density will not be carried forward to the more complex combination models.

7.2.3. Additional Combination Models

Combination Models														
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
R^2 Value	0.84	0.856	0.844	0.856	0.311	0.844	0.838	0.8	0.844	0.844	0.84	0.84	0.84	0.871
F Test	22.7 (.0002)	36.7 (.0001)	22.7 (.0002)	36.7 (.0001)	3.3 (.06)	22.7 (.0002)	21.65 (.0002)	16.8 (.0005)	22.7 (.0002)	16.7 (.0006)	16.8 (.0006)	16.8 (.0006)	16.8 (.0006)	19.6 (.0007)
DOF	11	12	11	12	11	11	11	11	10	10	10	10	9	10
1. ln*LSW*	-0.26	-0.42	0.7	0.626	0.54				-0.26		0.52	-0.4	-0.4	0.725
	0.46	0.007	0.004	3E-04	0.35				0.46		0.1	0.319	0.319	0.005
3. ln*Electrical*	0.961	1.046				0.7	0.77		0.96	0.52		0.92	0.92	
	0.001	1E-04				0.004	0.001		0.001	0.1		0.003	0.003	
4. ln*Elec Density*			0.962	1.05		0.26		0.98	0	0.4	0.92		0	1.211
			0.001	1E-04		0.46		0.003	0	0.32	0.003		0	0.002
5. ln*SHP*					0.67		0.12	0.65		0.25	0.25	0.25	0.25	
					0.27		0.67	0.017		0.41	0.41	0.41	0.41	
6. ln*OutfitDen*														1.45
														0.13
7. SurfCombat	0.17		0.17		0.44	0.17	0.35	-0.83	0.17	-0.09	-0.09	-0.09	-0.09	-0.9
	0.62		0.62		0.61	0.62	0.09	0.007	0.62	0.85	0.85	0.85	0.85	0.24

coefficient
p-value

Figure 26. Multiple variable model runs

Figure 26 shows fourteen additional models that were generated. Models with insignificant F-statistics were immediately discarded. Then any combination model with a variable p-value greater than 0.05 were not used, since a model with an insignificant coefficient would not be the best model to predict outcome. That removed all models with the exception of model 12, 13, 14, and 18. Model 14 was selected to be the best model because it had the highest F-value and R^2 value with uncorrelated variables. Models 12, 13 and 18 all had variables that were highly correlated with one another as shown in Figure 24.

The result for the best overall regression model is summarized below:

Model

$$lnCost_9 = .626 lnLSW + 1.05 lnElecDensity + 1.129 \tag{14}$$

Where

- $lnCost_9$ is the natural log of cost for the ninth unit in thousands of dollars
- $lnLSW$ is the natural log of light ship weight in tons
- $lnElecDensity$ is the natural log of the Electric Power Density in KW/LT

If compared, one could argue that the difference between Model 14 and Model 6 are so slight that it does not make much difference. The addition of light weight ship as a variable in Model 14 was only a small improvement in regression than adding a dummy variable to distinguish between surface combatants and non-surface combatants in Model 6.

The full multivariable regression analysis is found in Appendix A.

Based on the results of the multivariate analysis, lightship weight and electric power density has the best explanatory power for cost. This is in agreement with the 2006 RAND results. Additional variables such as outfit density and shaft horsepower did not statistically improve the CER.

8. Additional Observations

8.1 Cost per Ton relationship with Outfit Density

A common unit of measure for prices of commercial ships in shipbuilding industry is cost per ton. Some investment articles use cost per ton of ships to evaluate shipbuilding market prices.[45] Other cost estimating papers define ship unit cost as dollars per ton. A 2004 paper published by the Polish Maritime Research defines a new CER using dollars per ton.[46] And a

[45] Tao, "Ship-Building Industry Expects Demand to Rise CCTV News."
[46] Michalski, "Parametric Method of Preliminary Prediction of the Ship Building Costs."

2008 Naval Postgraduate paper uses cost per ton to show the relationship between outfit density and cost for submarines.[47]

Outfit density for thirteen surface ships were plotted against cost per ton and shown in Figure 27. The extrapolated density data and estimated cost per ton for the Korean KDX-III and Japanese Kongo ships, as described in section 4.6, were also overlaid onto the graph in blue.

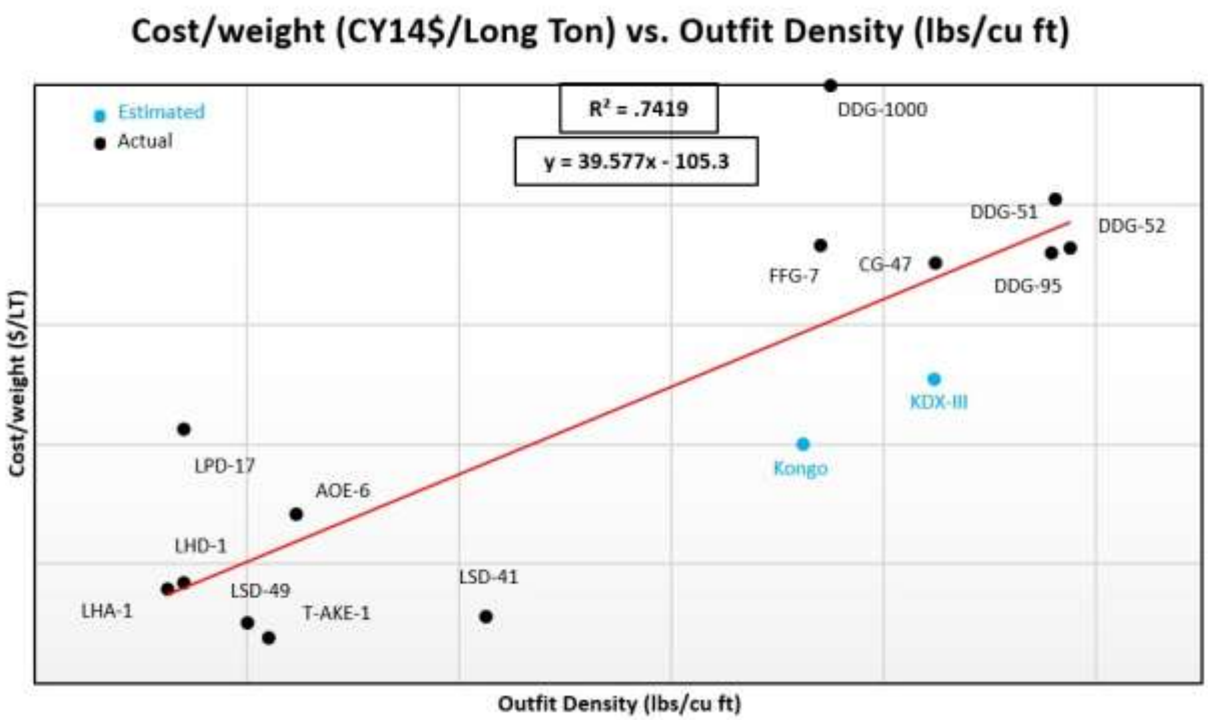

Figure 27. Cost/weight vs. Outfit Density

The results for the regression analysis shows a R^2 value of 0.7419 and a p-value of 0.0002. This analysis shows outfit density to be a good predictor for cost per ton. As density increases, the unit cost of naval ships also increase. This regression equation omits the estimated data points of the Kongo and KDX-III class.

[47] Grant, "Density as a Cost Driver in Naval Submarine Design and Procurement."

Notice the DDG-1000 is way above the regression line because of its high cost. The Korean KDX-III and the Japanese Kongo class ship were estimated and added to the chart to show that they operate below the regression line because they were cheaper and less dense than the DDG51 class ship. The ships that fall below the regression line are ships that cost less than the expected ships of comparable outfit density. Take for example, T-AKE which is below the line and was constructed below the budgeted cost. Ships that are above the line such as the DDG-1000 are ships that cost more than the expected cost of ship of similar density.

The measure of cost per ton can also be interpreted as a sort of mission premium, or how exotic their capabilities are. As ship's installed capabilities increase, the cost per ton increases as well. A ship that is above the regression line tend to be more exotic than ships that fall below the regression line.

8.2 Normalized Cost relationship with Electric Density

Electric power density for 13 surface ships were plotted against cost per ton and shown in Figure 28. The estimated cost per ton for the Korean KDX-III and Japanese Kongo ships were overlaid onto the graph in blue.

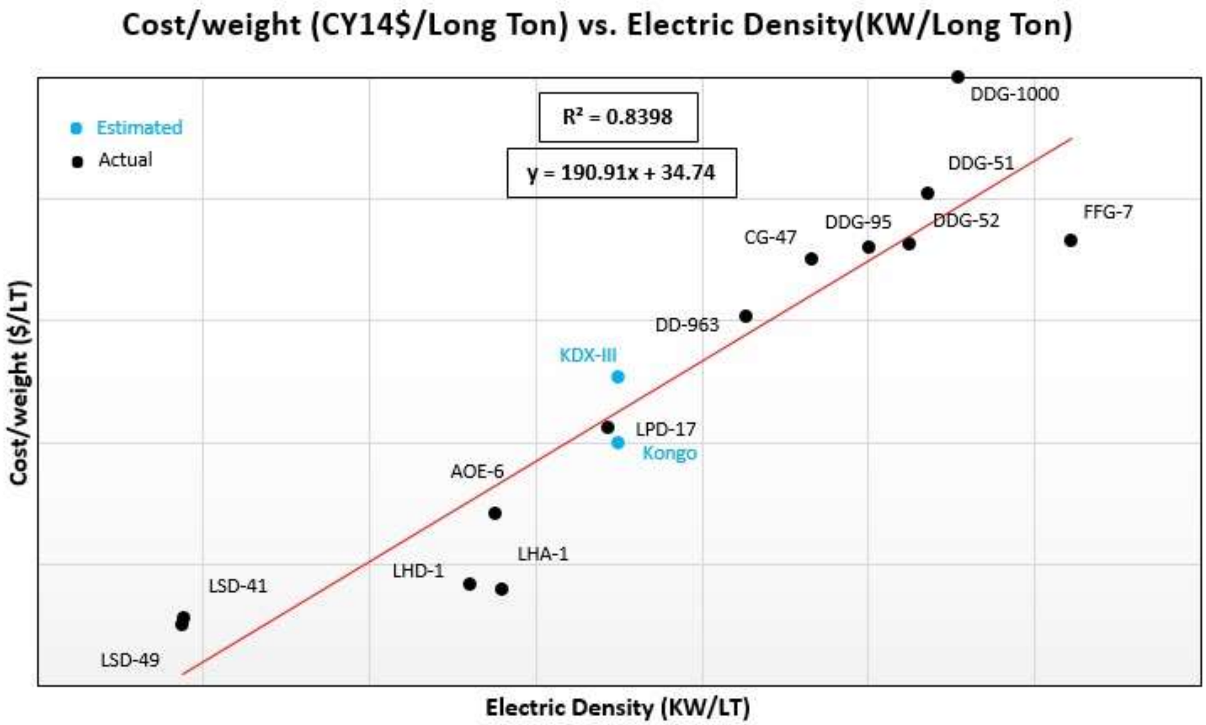

Figure 28. Cost/weight vs Electric Density

The cost per ton vs electric density plot in Figure 28 shows even stronger regression fit with a R^2 value of .8398 and P-value of less than 0.0001. Again the international ships were not factored into the regression equation. This regression shows a positive relationship between electric density and cost per ton. In another words, as ships increase in electrical complexity, their cost per ton increases.

But there must be some caution before making the connection between densityand cost. In Figure 27, there is a marked difference between surface combatants and non-surface combatants. They are at opposite ends of the outfit density scale and are grouped together. If the dataset was split between these two different types of naval ships, we would unlikely be able to get a significant relationship between cost per ton and outfit density. In addition, Figure 28 has light ship weight in the denominator of both axes. Cost per ton was determined by taking the procurement cost and dividing it by light ship weight, and electric density was calculated by taking electrical generation capacity and dividing it by light ship weight.

But Figure 27 and 28 show a very strong relationship between outfit density and electric density with cost per ton, which had not been previously compared for surface ships.

9. Summary, Conclusions and Recommendations

1. **Weight alone is a weak predictor of overall cost.**

   Using the dataset (mixed surface combatant and non-surface combatant) and methods in this paper, we see a weak relationship at best between light ship weight and overall cost. Ship designers and policy makers should consider that for naval surface ships, with all else being equal, building a marginally smaller ship could increase costs due to increased density and the associated design and construction challenges.

2. **Electrical power generation (or electric density) combined with weight is a much better indicator for overall cost than weight alone.**

   Electrical power density and light ship weight together are significant predictors of cost with coefficient for light ship weight at 0.626 and power density at 1.05. The regression analysis for electric density and weight resulted in a R^2 value of 0.856 with F-test of 36.7 (P-value of .0001) as compared to a R^2 value of 0.29 and F-test of 4.123 (P-value of .04) for the weight-only regression analysis.

3. **Outfit density and electric density has a positive relationship with ship cost per ton.**

   Outfit density and electric power density are very good indicators and are positively related with ship cost per ton. As density of ship increases, cost per ton increases. This can be very useful to ship designers and policy makers. In the past, weight-based CER constrained ship size with the idea that lighter and smaller ships were cheaper. Although this is true in a broad sense (bigger ships tends to cost more), with all things equal, when you shrink the hull size of a ship for a given class, you increase density. Increasing density will increase cost per ton for naval ships. As seen by international destroyers in Section 4.6 on page 38, reducing density can help reduce the cost of naval ships.

4. **The best CER includes weight and electrical power density.**

The regression analysis resulted in a new CER equation expressed below.

$$lnCost_9 = .626lnLSW + 1.05lnElecDensity + 1.129$$

Where

- $lnCost_9$ is the natural log of cost for the ninth unit in thousands of dollars
- $lnLSW$ is the natural log of light ship weight in tons
- $lnElecDensity$ is the natural log of the Electric Power Density in KW/LT

5. **Density is not the silver bullet for ship cost estimation.**

Density does not fully encompass the major costs for naval ships but only explains part of the growing costs of Navy ships. The other factors explained by the Secretary Ray Spear in Section 1 of the paper and the 2005 GIBBS study shows many layers that cause cost growth.

6. **The practice of using cost estimation based solely on weight must change.**

The practice and idea that weight is an adequate early predictor of ship cost should change in the acquisitions world. Although many engineers and cost analysis fully understand the imperfections of a weight based cost estimation, policy makers should understand that weight alone does not drive the majority of ships' cost and should take into account additional factors such as density and complexity.

9.1. Conclusion

This paper quantified density and complexity using outfit density and electric power density. A new CER was developed based on electric power density and light ship weight. This paper also showed the relationship between outfit density and electric power density vs. cost per ton for naval surface ships. This paper attempted to show sufficient reason to move away from a purely weight-based cost estimating relationship still in use in industry and academia, and introduce density as a significant factor in cost. Outfit density was not quite significant as a cost predictor in this analysis, but warrants further exploration with additional, more detailed data.

We know that early stage cost estimation from a parametric top-down level is an inexact science. Through development of a new CER, this paper shows evidence that adding density can improve the uncertainty of early stage cost estimation for Navy ships. There are currently several outside efforts and research on density-based cost estimation for integration into software used by naval architects. There exists much potential for further work to improve on the Navy's parametric cost estimating method.

The following are recommendations for future work to be done within cost estimating relationships.

- Using full access to NAVSEA05C's database, further develop density-based CERs.
- Explore other measures of density, such as permeability data for surface ships and develop regression models for a new CER or adjustment factors similar to CGT calculations.
- Incorporate a robust and multi-variable based CER into the Navy's ship design software, ASSET.

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Appendix A. Multivariable Regression for ship cost

Summary of Fit

RSquare	0.88003
RSquare Adj	0.856036
Root Mean Square Error	0.224715
Mean of Response	13.81129
Observations (or Sum Wgts)	13

Analysis of Variance

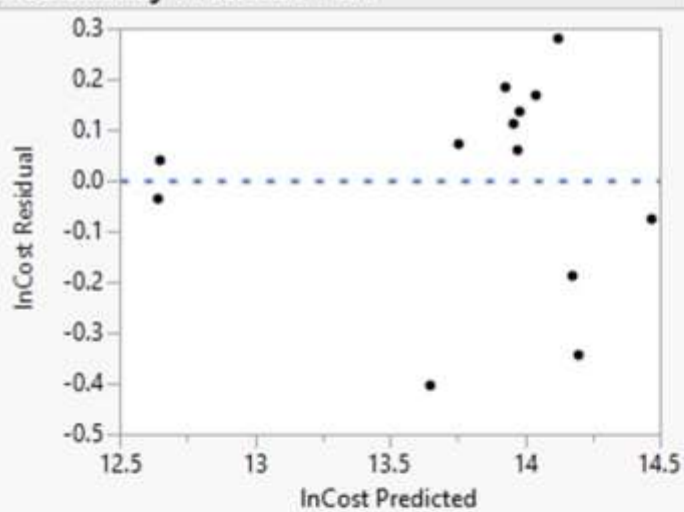
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	3.7041693	1.85208	36.6771
Error	10	0.5049704	0.05050	Prob > F
C. Total	12	4.2091397		<.0001*

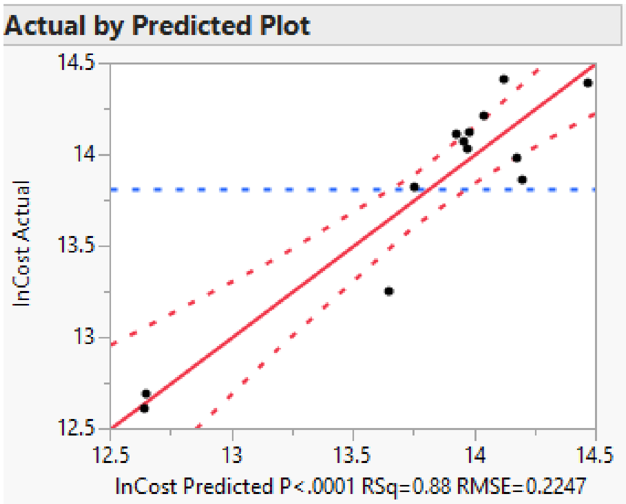
Parameter Estimates

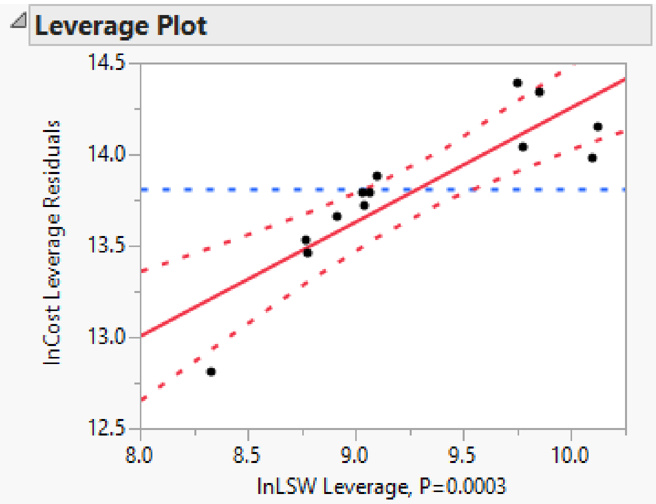
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.1291184	1.606617	0.70	0.4982
lnLSW	0.6255611	0.113534	5.51	0.0003*
lnElec Density	1.0458206	0.125351	8.34	<.0001*

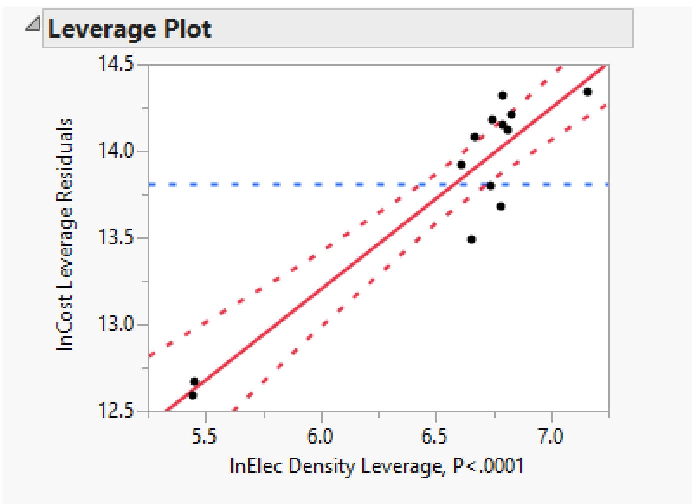
Effect Tests

Residual by Predicted Plot




Actual by Predicted Plot
14.5
14
13.5
13
12.5
lnCost Actual
12.5
13
13.5
14
14.5
lnCost Predicted P<.0001 RSq=0.88 RMSE=0.2247


Leverage Plot
14.5
14.0
13.5
13.0
12.5
lnCost Leverage Residuals
8.0
8.5
9.0
9.5
10.0
lnLSW Leverage, P=0.0003


Leverage Plot
14.5
14.0
13.5
13.0
12.5
lnCost Leverage Residuals
5.5
6.0
6.5
7.0
lnElec Density Leverage, P<.0001

Appendix B. Cost vs. Light Ship Weight of Surface combatants Regression

Summary of Fit

RSquare	0.812135
RSquare Adj	0.785297
Root Mean Square Error	351.2571
Mean of Response	1177.538
Observations (or Sum Wgts)	9

Analysis of Variance

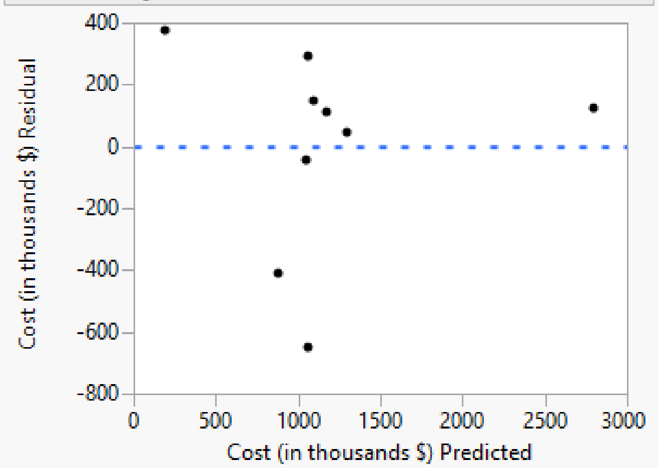
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	3733631.7	3733632	30.2609
Error	7	863671.0	123382	Prob > F
C. Total	8	4597302.7		0.0009*

Parameter Estimates

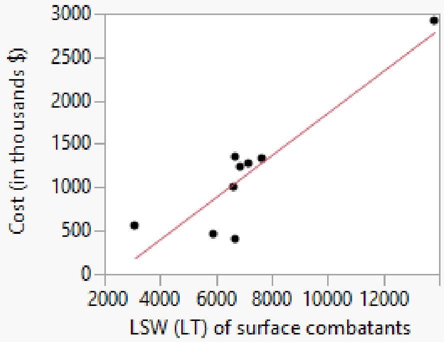
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-557.0033	336.3515	-1.66	0.1417
LSW (LT) of surface combatants	0.242228	0.044034	5.50	0.0009*

Effect Tests

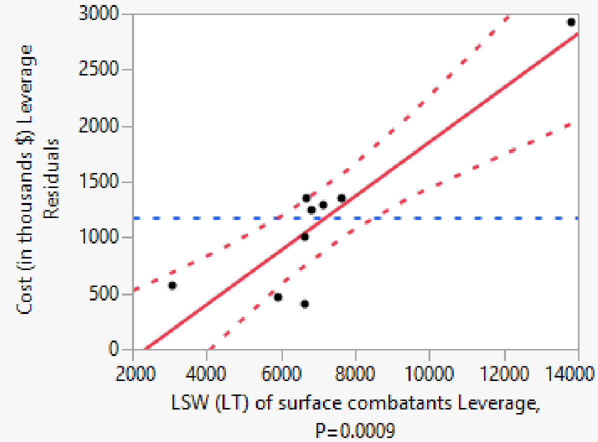
Residual by Predicted Plot



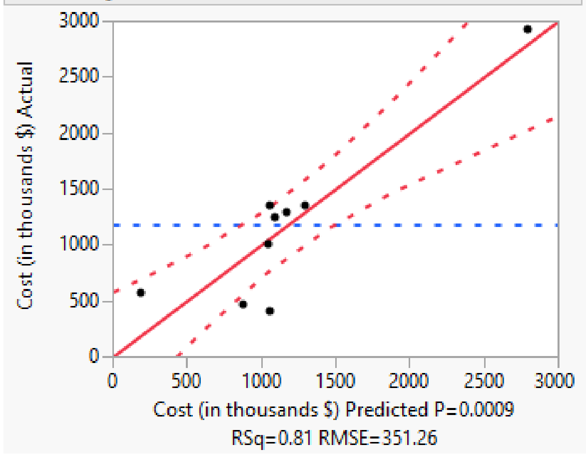
Regression Plot



Leverage Plot



Actual by Predicted Plot



Appendix C. Production in the Innovation Economy Study

This research is conducted under a bigger umbrella research project at MIT called Production in the Innovation Economy (PIE). This fairly recent research is focused on bringing innovation back to the American economy through research and manufacturing[48]. Founded in 2010 at MIT as a three year project involving over twenty professors, the PIE study seeks to analyze how innovation moves to market, specifically how production capabilities, industrial acceleration, and manufacturing innovation creates more jobs and sustainable growth in the U.S. This includes fields from energy, life sciences, transportation, environment, communication, construction, and security.[49]

In spring of 2012, the Assistant Secretary of the Navy in Research, Development and Acquisition, Secretary Sean Stackley visited MIT and started the study, Production in the Innovation Economy: How to Create Excellence Through Competition and Benchmarking in the U.S. Shipbuilding and Defense Industry. This two year study tasks MIT to explore processes and opportunities to optimize production in the area of U.S. shipbuilding and defense manufacturing. The study is split into 5 tasks, (1) Innovation in Bidding and Contracting, (2) Project Management and Rework Dynamics, (3) National and International Benchmarking of U.S. shipbuilding Performance, (4) Supply Chain Management and Supplier Base, (5) Prospects for U.S. Commercial Shipbuilding. To date, several theses have been written in Tasks 1 and Task 2 and this thesis will fall under the Task 3, National and International Benchmarking of U.S. Shipbuilding Performance.

[48] Dizikes and Office, "MIT Report Identifies Keys to New American Innovation - MIT News Office."
[49] "Production in the Innovation Economy (PIE)."

It is important that Secretary Stackley is the sponsor of this study. Many parties from industry and government have been very supportive in helping gather information and opening doors for them. For example, NASSCO in San Diego has been very generous with their time and effort in giving as much information about their shipyard during our visit there.

Appendix D Shipyard Visits

During the course of conducting research and becoming familiar with naval shipbuilding, two shipyards were visited, National Steel and Shipbuilding Company (NASSCO) and Bath Iron Works. Although they are not directly related to the thesis topic of cost estimation, the insight obtained from the visit was reason enough to include these shipyards in the appendix.

NASSCO – General Dynamic

In August 2013, a three man team from the MIT PIE study visited NASSCO shipyard in San Diego for a tour and visit. This San Diego shipyard is the only full service shipyard in the wast coast of the United States.

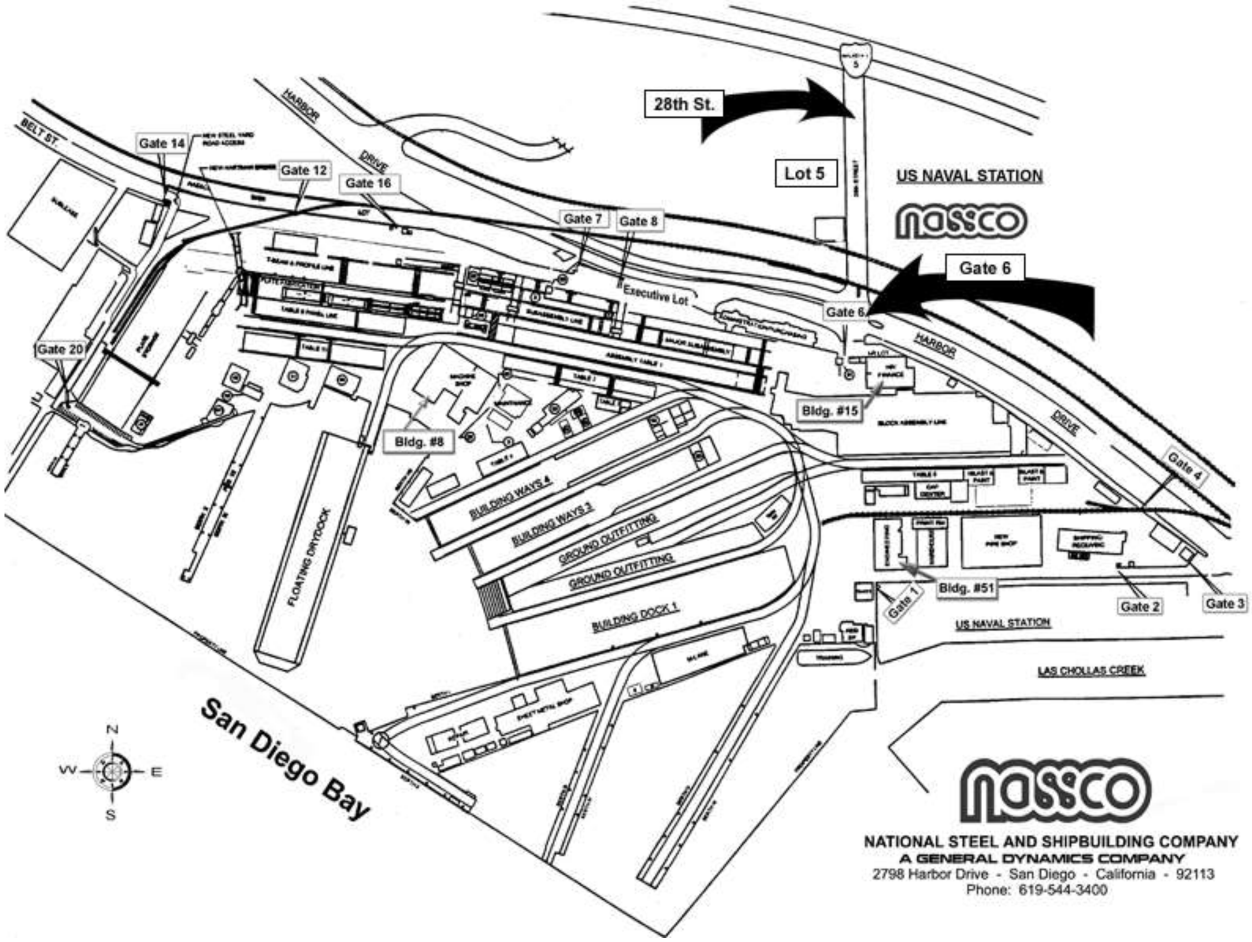


Figure 29. NASSCO San Diego[50]

Its roots trace back to 1905 as a small machine shop called, California Iron Works. It later become National Iron Works in 1922, then in 1949 became National Steel and Shipbuilding Co.[51] In 1998 General Dynamics bought out NASSCO and went through a large facilities upgrade. As one of the country's largest shipyard, NASSCO builds commercial cargo ships and tankers and Navy support and military sealift ships.

[50] "General Dynamics NASSCO: Maps and Directions."
[51] "San Diego-Based NASSCO's History to Date | The San Diego Union-Tribune."

Naval Ships

In 2012, NASSCO delivered the last of the fourteen T-AKE ships, the USNS Cesar Chavez to the US Navy. The T-AKE ships are a dry cargo/ammunition ship designed to operate independently for extended periods at sea for replenishment services. From 1993-2002, NASSCO built eight medium-speed, roll-on/roll-off (RO/RO) ships and three conversions for the Military Sealift Command. In the past, NASSCO has built AOEs, hospital ships, logistics ships, cable repair ships, tenders, oilers, and even landing ships. In May 2011, NASSCO received $744 million contract to build the first two Mobile Landing Platform (MLP) ships for the U.S Navy. The first MLP-1 was delivered in May 2013 and the second and third MLP ship will be delivered in 2014 and 2015. The MLP is a unique semi-submersible, flexible and modular platform for logistical movements to reduce dependency on foreign ports. This program is highly successful and rides on the valuable lessons learned and success of the T-AKE program. NASSCO has been praised for building these ships on time and within budget.[52]

Commercial ships

NASSCO is currently the largest commercial ship producer in the United States. They have designed and built fifty three commercial ships since 1960. The latest commercial contract is the construction of four American Petroleum Tanker (APT) LNG-conversion-ready ships. It is currently producing two TOTE TEU LNG powered containerships in conjunction with Daewoo Shipbuilding & Marine Engineering (DSME), a Korean shipbuilding company in Busan, South

[52] General Dynamics, "General Dynamics - NASSCO, U.S. Navy Design and Construction."

Korea. In the past, NASSCO has built PC-1 Product Tankers, BP Tankers, TOTE Trailerships, and dozens of other types of tankers and container ships.[53]

Bath Iron Works – General Dynamics

In early August 2013, a group of students and conference attendees from the MIT 2N Professional Summer Shipbuilding Operations and Technology course made a site visit to Bath Iron Works in Bath, Maine. During the tour, the shipyard workflow was observed, walking through all the facilities from fabrication to assembly and welding. Bath Iron works is one of the oldest naval shipyards in America. Its history begins in 1890 when the Cottage City, a coastal passenger transport was built for the Maine Steamship Co. Since then Bath Iron works have built more than 425 commercial ships and 245 military ships. In 1995, Bath Iron Works was bought out by General Dynamics.

[53] "General Dynamics/NASSCO: Commercial Design and Construction."

Figure 30. Bath Iron Works - General Dynamics

Naval Shipbuilding

Bath Iron works has a rich history of building quality naval ships. They built the T.A.M. Craven and USS Dahlgren, torpedo boats during the World War I era and was responsible for building 20% of all new destroyers that were delivered to the US Navy during World War II. They delivered superior quality naval ships and enjoyed high praise and reputation for their work.[54]

Starting 1973, Bath Iron Works built and delivered 24 Oliver Hazard Perry Class (FFG 7) Guided Missile Frigates. And from 1982, Bath Iron Works have built eight Ticonderoga (CG 47) Class AEGIS guided missile cruisers. In 1985, Bath Iron Works (along with Northrop Grumman Ship Systems, Pascagoula) was awarded the construction of the USS Arleigh Burke (DDG 51)

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[54] Steiner, “Bath Built Is Best-Built.”

class Destroyer. Over the next 30 years, they have built over 30 follow-on ships and will continue to build the latest flight of the Arleigh Burke Destroyers into the next decade. [55] The next generation navy Destroyer, Zumwalt class DDG-1000 is currently being built at Bath Iron Works. The lead ship is expected to be delivered in late 2014. On April 12th 2014, the USS Zumwalt was christened at Bath Iron Works.

[55] General Dynamics, "History | General Dynamics Bath Iron Works."

Appendix E Case Studies

Zumwalt Class DDG-1000

Figure 31. Ultra Unit section of DDG-1000.

The next generation DDG-1000 program started in the early 1990's and was designed to improve the Navy's naval surface fire support (NSFS) and operations in littoral waters. It would also have the latest technology such as the electric drive propulsion system and a stealth hull to minimize radar cross-section. It was designed for a lower life cycle cost and designed automation technologies that allowed for a reduced manning of about 142 sailors.[56]

[56] O'Rourke, "Navy DDG-51 and DDG-1000 Destroyer Programs: Background and Issues for Congress."

The Navy originally envisioned plans to procure 16-24 DDG-1000's, but in February 2006, reduced that number to 7. In 2007, the Navy was provided funding to build the first two ships by Bath Iron works. But in 2008, the Navy announced the cancellation of the DDG 1000 program because of high costs, and chose to restart the Arleigh Burke DDG-51 class ships. Finally, in August 2008, the Navy decided on providing funding for a third Zumwalt class destroyer reducing the total number of DDG-1000 ships from 24 down to 3. This reduction had an impact on the cost growth of the DDG-1000 program since it reduced the allocation spread of class-wide procurement costs. From the budget request of 2009 until 2015, the procurement cost of the three Zumwalt class ships rose by $3,092.3 million or 34.4%. [57]

Change in Estimated Combined Procurement Cost of DDG-1000, DDG-1001, DDG-1002 $ in millions			
	Estimated Combined procurement cost	Change from prior year	Cumulative Change from 2009 Budget
FY 2009 budget	8,977.10	-	-
FY 2010 budget	9372.5	395 (+4.4%)	396 (+4.4%)
FY 2011 budget	9993.3	620.8 (+6.6%)	1016.2 (+11.3%)
FY 2012 budget	11308.8	1,315.5 (+13.2%)	2331.7 (26.0%)
FY 2013 budget	11470.1	161.3 (+1.4%)	2493.0 (+27.8%)
FY 2014 budget	11618.4	148.3 (+1.3%)	2641.3 (+29.4%)
FY 2015 budget	12069.4	451.0 (+3.9%)	3092.3 (+34.4%)

Figure 32. Cost Growth for DDG-1000[58]

[57] Ibid.
[58] Ibid.

Case Study LPD-17

Figure 33. LPD-17

The San Antonio Class (LPD-17) is the Navy's latest amphibious class ship. Amphibious ships are designed to transport and carry Marines to conduct expeditionary landings on beaches and other coastal landing areas. Two types of amphibious ships exist in the U.S. Navy, "big deck" amphibious assault ships, LHA and LHD and a bit smaller "small deck" LSD or LPD. In the LPD, L stands for landing platform, P for helicopter platform, and D for well deck. Amphibious ships have large capacity for cargo and equipment, and allows the landing crafts and helicopters to transport troops, equipment, and supplies from ship to shore without a separate port facility. Because of their vast capability, they are useful in both war and non-wartime situations. They have been used for humanitarian assistance disaster relief (HA/DR), peacetime engagements and partnership-building and nation-building activities, reconstruction operations, peace-enforcement operations, non-combatant evacuation operations (NEOs), anti-piracy operations, and counter-terrorism operations. The amphibious ship with their embarked marines provides the United States a strong forward presence.[59]

Cost Growth for LPD-17 and Construction Problems

The LPD-17 was first procured in FY 1996 for $954 million and experienced a two-year delay in design and construction. It was delivered to the US Navy in 2005 at a cost of $1,758 million, a staggering $850 million difference or cost growth of 84%.

LPD-17 Class growth in Budget ($ in million)			
	Initial	FY2005	Total Difference
LPD-17	$954	$1,758	804 (84%)
LPD-18	$762	$1,011	249 (33%)
Total	**$1,716**	**$2,769**	**$1,053**

Figure 34. LPD-17 Cost Growth[60]

The Navy accepted the ship in 2005 with 1.1 million hours of construction work still remaining to be done. Even as the LPD-17 was commissioned into service in Jan 14th 2006, it had thousands of construction deficiencies. There were many complaints to Northrop Grumman Ship Systems and to the Navy leadership. Some of the mission packages were still not fully running even after almost 2 years of being commissioned. In 2008, its first deployment was delayed by two days due to hydraulic system problems of the stern gate. More troubling was the lube oil

[59] O'Rourke, "CRS Report for Congress. Prepared for Members and Committees of Congress," -.
[60] United States Government Accountability Office, "Defense Acquisitions. Improved Management Practices Could Help Minimize Cost Growth in Navy Shipbuilding Programs."

leaks discovered during its deployment causing the ship to be under two weeks of maintenance in Bahrain. In early 2010, the LPD-17 experienced problems with the lube oil system, this time with excessive contaminants in the lube oil system. During its maintenance period in Bahrain, weld problems were discovered in the ship. The thickness of many welds were not meeting the military specifications and caused some pipe hanger welds to fail, and could decrease the service life of the ship. As a result, all pipe welders at the shipyard at Northrup Grumman were de-certified and retrained. In late 2010, engineers discovered the main engines and reduction gears were improperly installed causing excessive vibrations and potential damage. Several times the Judge Advocate General (JAGMAN) conducted an investigation for any gross neglect from the shipyard or the Navy. They concluded that inadequate workmanship, poor quality control during construction, shortcomings in the ship's design and inadequate managements of engineering problems were the cause of LPD-17's issues.[61]

[61] O'Rourke, "CRS Report for Congress. Prepared for Members and Committees of Congress," -1.

Case study LCS-1/2

Figure 35. LCS 1 (Lockheed Martin Design, Top),
LCS 2 (General Dynamics Design, Bottom)

The Littoral Combat Ships (LCS) is the latest class of ships that have undergone major financial troubles. The initial plan for the Navy was to procure 52 LCSs which accounts for about one-sixth of the planned 306 ship Navy. These smaller and modular ships have the capability to replace the overqualified roles that current Destroyers and Cruisers have been performing such as anti-piracy and anti-drug operations. In general, the LCS ships are designed to have "plug and fight" mission packages that includes antisubmarine warfare (ASW), mine countermeasures (MCM), and surface warfare (SUW). Additional potential capabilities include

Intelligence, surveillance, and reconnaissance (ISR) operations, maritime security and intercept operations, anti-piracy operations, support of Marines or Special Operations, and homeland defense operations. It has a maximum speed of 40 knots and about 3000 tons, making it similar to size of a Coast Guard cutter. Its shallow draft allows it to operate closer to inland waters and pull into ports that are not accessible to larger Navy ships. The LCS was designed to meet the future needs of the coastal and open water threats of the times. There are even potential plans for adding an array radar and tomahawk missile capability to increase the threat and lethality of future LCS.[62]

There are two variants of the LCS in production. In 2004, the Navy awarded contracts to both Lockheed Martin and to General Dynamics to design and build two different designs. The Lockheed design was an aluminum semi-planning monohull while the General Dynamics design was an aluminum trimaran hall. There has been some criticism regarding the Navy's decision to go with two variants due to the increased cost of maintenance, training and accessions. But production continues with both variants of the LCS ships.

In February 24th 2014, the Secretary of Defense, Chuck Hagel announced that the DoD intends on reducing the total number of LCS ships from 52 ships to 32 ships. This news was not surprising since the military is currently going through a series of budget cuts with the LCS program going through its own cost growth between 2005 and 2013 budgets.

[62] O'Rourke, "Navy Littoral Combat Ship (LCS) Program: Background and Issues for Congress."

Littoral Combat Ships (LCS) Cost Growth Budget estimate for lead ship (in $ million)		
	LCS 1	LCS 2
2005	215.5	213.7
2006	212.5	256.5
2007	274.5	278.1
2008	375	375
2009*	631	636
2010*	637	704
2011*	656	736
2012*	670.4	808.8
2013*	670.4	813.4

*including outfitting and post-delivery and Final System Design Mission Systems and Ship Integrating team

Figure 36. LCS Cost Growth[63]

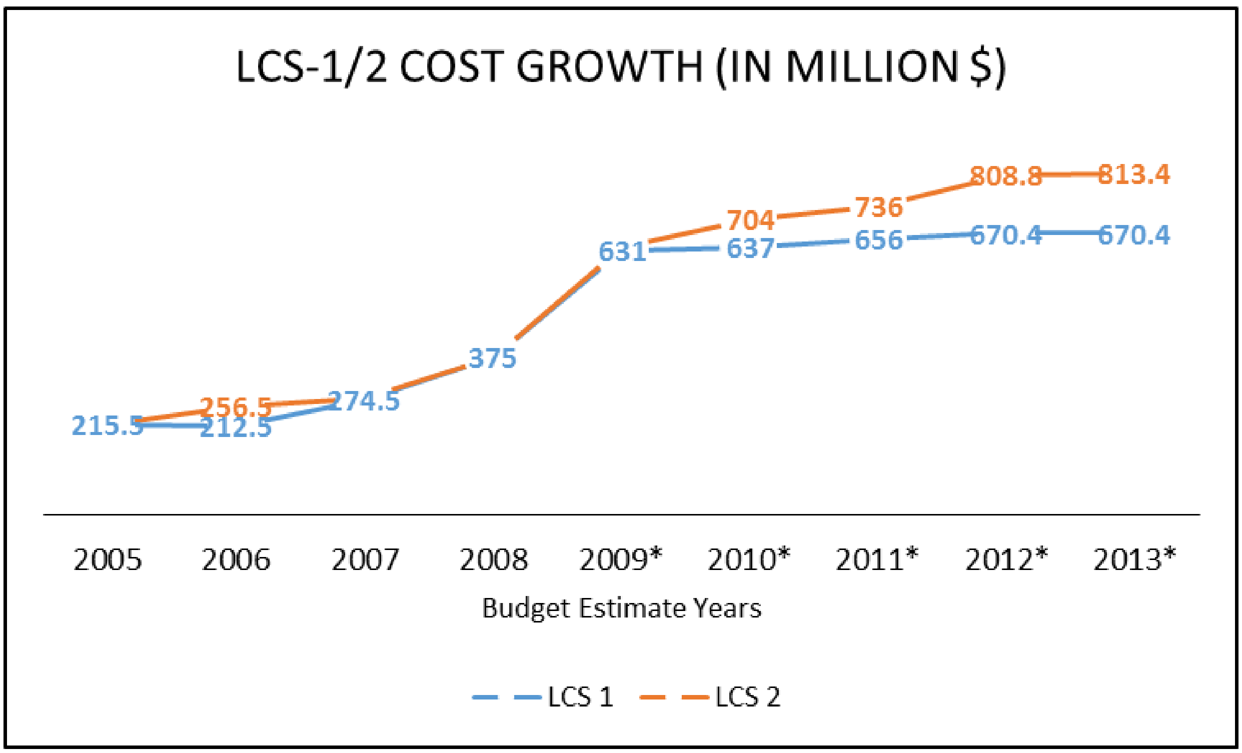

Figure 37. LCS 1/2 Cost Growth according to Budget Years

[63] Ibid.

One of the reasons for this major cost growth is the unrealistic low original estimate. This is considered a low-balling strategy, where an unreasonable low estimate was submitted just to win approval.

The Congressional Budget Office's Fiscal Year 2008 Shipbuilding plan proposed a cost-to-weight relationship to estimate the cost of the lead LCS ship. They used the cost-to-weight ratio of the lead Oliver Hazard Perry class frigate as an analogy and determined that the LCS-1 would be expected to cost about $470 million.[64] This number was closer to the actual cost of the lead LCS ship than what the Navy had originally estimated.

[64] Congressional Budget Office, "Resource Implications of the Navy's Fiscal Year 2008 Shipbuilding Plan."

Appendix F Overview of Commercial Shipbuilding Industry

The Commercial Shipbuilding industry in the United States holds a very tiny portion of the world's shipbuilding market share. The commercial industrial base and the U.S. Merchant Marine is protected only by the Jones Act of 1920[65], which requires vessels conducting trade between U.S. ports to be U.S. flagged and built by U.S. shipyards. In addition, it must be owned by a U.S. citizen and crewed by American merchant marines[66]. Up to 1981, the U.S. government subsidized customers the high price of U.S. built ships to sustain the small commercial industry and attract people to buy U.S. built ships. But since, there has been little incentive for the growth of the U.S. commercial shipbuilding industry. In fact, as of 2012, the United States had only 0.7 percent of the world's commercial shipbuilding orders as seen in Figure 1. And had built only 138,000 gross tons, which contributed to only 0.1 percent of the world's commercial ship production. When converted into compensated gross tonnage, the United States held only 0.4% of the world's market share in commercial shipbuilding in 2013.[67]

[65] "Text of the Jones Act."
[66] "The Jones Act - Foundation of the Merchant Marine."
[67] "Shipbuilding Statistics." March, 2013. The Shipbuilders' Association of Japan http://www.sajn.or.jp/e/statistics/Shipbuilding_Statistics_Mar2013e.pdf

World New Orders			
2012			
Country	Number	GT (thousands)	Share (%)
Japan	356	8,414	21.9
South Korea	230	12,034	31.3
China	628	14,131	36.8
Belgium	0	0	0
Denmark	5	3	0
France	6	229	0.6
Germany	11	416	1.1
Greece	0	0	0
Italy	4	110	0.3
Netherlands	19	48	0.1
U.K.	5	2	0
Finland	2	109	0.3
Norway	26	116	0.3
Sweden	0	0	0
Spain	13	82	0.2
Portugal	0	0	0
Europe Total	91	1,114	2.9
Brazil	55	738	1.9
Poland	25	72	0.2
Singapore	16	48	0.1
Taiwan	9	63	0.2
U.S.A.	**58**	**257**	**0.7**
Croatia	7	46	0.1
India	37	144	0.4
Philippines	8	405	1.1
Romania	43	227	0.6
Turkey	46	109	0.3
Vietnam	53	117	0.3
Others	264	510	1.3
Sub Total	621	2,737	7.1
World Total	1,926	38,430	100

Figure 38. World New Orders[68]

[68] Ibid.

Global Market Share 2012 (Compensated Gross Tonnage)	
China	41.1
South Korea	29.4
Japan	17.7
Europe	5.4
Other	5.8
U.S.A.	0.4

Figure 39. Global Market Share in CGT 2012[69]

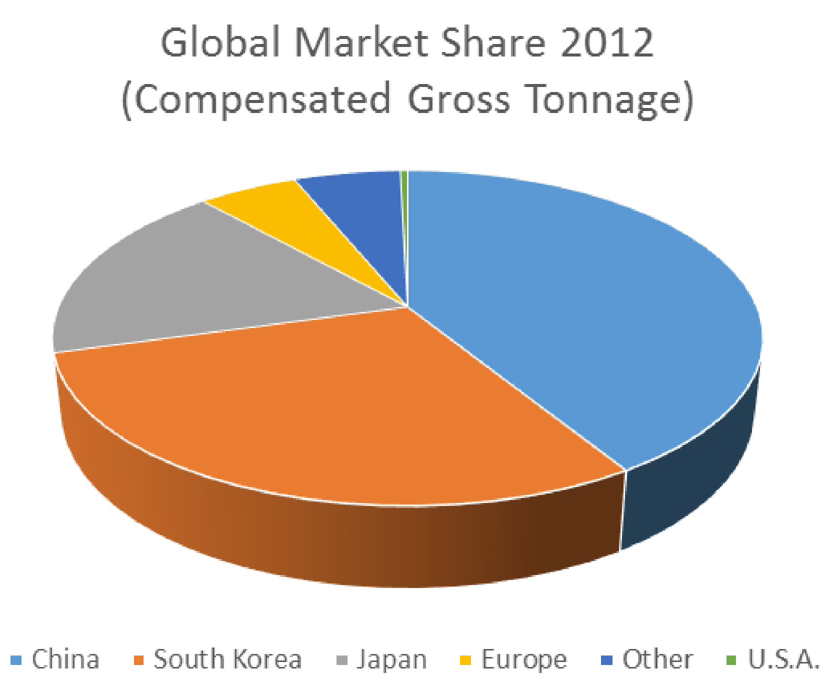

Figure 40. Pie Chart of Global Market Share 2012[70]

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[69] "World Shipyard Monitor 2013." Clarkson Research, March 2013
[70] Ibid.

It is clear from the global market share that China, South Korea and Japan dominate the world's market. Japan and South Korea have traditionally dominated the market for several decades but China in the last ten years has surged in the global shipbuilding market as seen in Figure 4. Just like Japan and Europe were threatened by the emerging South Korean shipbuilding industry several decades ago, there has been considerable churning within the Korean and Japanese shipbuilding industry due to the recent threat of Chinese shipbuilding.

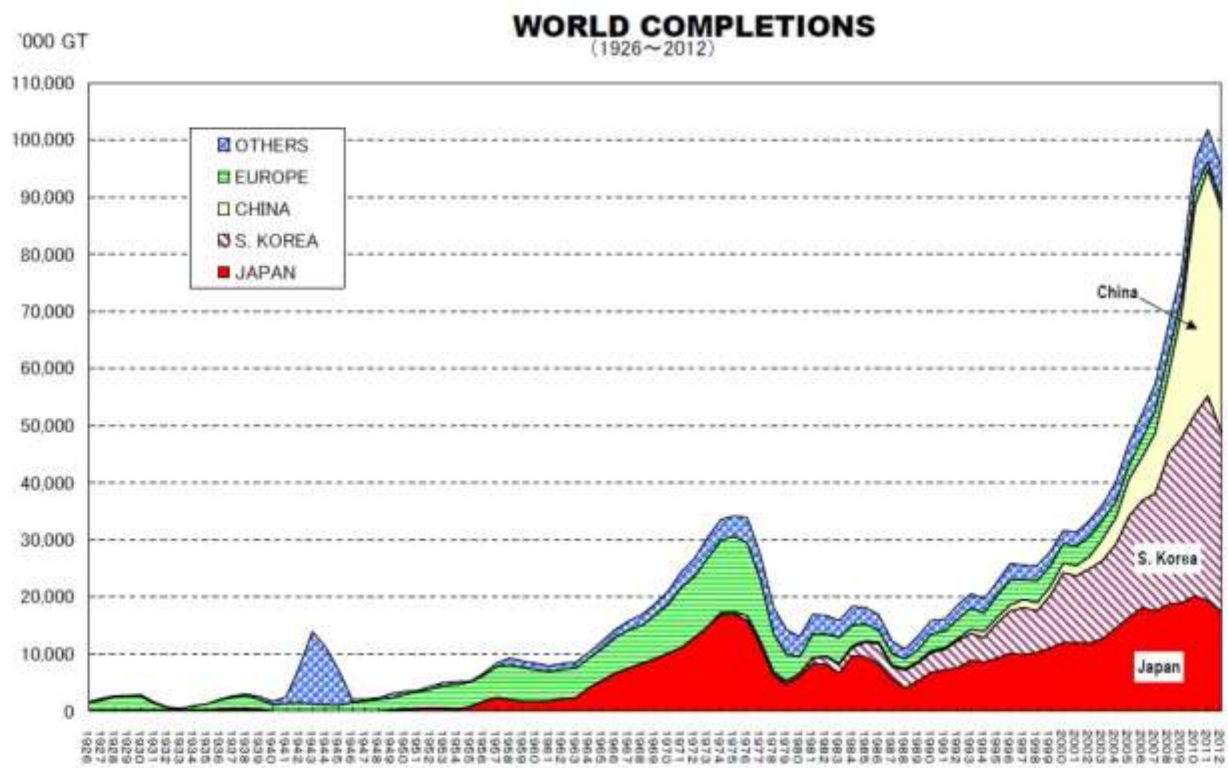

Figure 41. World Completions[71]

Figure 4 shows the dramatic rise in China's market share of the shipbuilding industry starting from the mid 2000's. China's economic boom had contributed significantly to their shipbuilding industry and they are now the leader in global shipbuilding by gross tonnage completed. There

[71] "Shipbuilding Statistics." March, 2013. The Shipbuilders' Association of Japan http://www.sajn.or.jp/e/statistics/Shipbuilding_Statistics_Mar2013e.pdf

has been some concerns within the industry regarding the stability and quality of ships produced in China.[72] It is clear that the most of the activity for world's shipbuilding is located in Asia and as a result, many of the latest technologies and process improvements have been implemented in those countries with high output.

[72] Collins and Grubb, "A Comprehensive Survey of China's Dynamic Shipbuilding Industry."

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